EFFECT OF WATER ON AXIAL FLOW COMPRESSORS. PART I. ANALYSIS AND ETC(U)

JUN 81 T TSUCHIYA; S N MURTHY

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EFFECT OF WATER ON AXIAL FLOW COMPRESSORS

PART I ANALYSIS AND PREDICTIONS

T. Tsuchiya
S.N.B. Murthy

Purdue University
School of Mechanical Engineering
West Lafayette, Indiana 47907

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Larry E. Crawford
Project Engineer
LARRY E. CRAWFORD
Compressor Research Group

WALKER H. MITCHELL
Chief, Technology Branch

FOR THE COMMANDER

James M. Shipman, Major, USAF
Deputy Director
Turbine Engine Division
Aero Propulsion Laboratory

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# Effect of Water on Axial Flow Compressors Part I Analysis and Prediction

**Title**: Effect of Water on Axial Flow Compressors Part I Analysis and Prediction

**Authors**: T. Tsuchiya and S.N.B. Murthy

**Performing Organization**: Purdue University, School of Mechanical Engineering, West Lafayette, IN 47907

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**Keywords**: Water Ingestion, Propulsion Control, Axial Compressors, Rain Effects, Gas Turbine Engines, Flight Control, Two-phase Flow, Compressor Performance

**Abstract**: The subject of air-water mixture flow in axial compressors of jet engines is of practical interest in two contexts of water ingestion: during take-off from rough runways with puddles of water and during flight through rain storms. The change in the compressor performance in turn produces changes in the performance of other components and of the engine as a whole. During the current investigation, (i) an analysis of the effects of water ingestion into a compressor has been carried out leading to the development of a predictive code, the PURDU-WICSTK program and (ii) a series of tests have been carried...
out on a small test compressor with mixtures of gases (containing methane gas to simulate steam) and with air-water droplet mixtures. The experimental results have been compared with predictions. It is concluded that the basic effects of water ingestion into compressors arise through (2) blockage, (b) distortion and (c) heat and mass transfer processes, the changes in blade aerodynamic performance being relatively small. In the case of a compressor of small mass flow and pressure ratio and high operating speed, increased quantities of water ingestion give rise to large quantities of water in the tip region. When the pressure ratio and air mass flow are large and the operating speed is correspondingly small, there arises a possibility of water evaporation, especially towards the hub, which gives rise to changes in gas phase mass flow and temperature. The changes in compressor performance are large at high speeds and high flow rates; there also arises a change in the surge characteristics. In light of the nature of changes produced by water ingestion, a preliminary analysis has been carried out on the possible changes in engine performance.
This final report presents the results of research undertaken at Purdue University under Air Force Contract No. F33615-78-C-2401. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3066, Task 306604 and Work Unit 30660454, with Mr. Larry E. Crawford, AFAPL/TBC, as Project Engineer.

Two earlier publications of direct relevance to the project are as follows:

1) "Water Ingestion into Axial Flow Compressor", Report No. AFAPL-TR-76-77, August, 1976; and


The research reported in the current report pertains to a further development of a prediction code for the performance of an axial compressor with water ingestion, experimental studies on a small engine-driven axial compressor with water ingestion and an analysis of the results.

The final report consists of three parts, Part I entitled Analysis and Predictions, Part II entitled Computational Program and Part III entitled Experimental Results and Discussion. Each part is presented in a separate volume.

Dr. Bruce A. Reese, currently Chief Scientist at the Arnold Engineering Development Center, Arnold Air Force Base, who was Professor and Head, School of Aeronautics and Astronautics, Purdue University, up to June 30, 1979, participated in the conduct of research from January, 1978 until June 30, 1979.

The Drive Engine and the Test Compressor provided by the Air Force for the experimental studies under this project were manufactured by the Detroit Diesel Allison of Indianapolis. They refurbished the units during this program under a subcontract. In that work and in a variety of ways the DDA and several of their personnel have been most helpful and have given their time and advice generously to the investigators.
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 Comparison of Properties for Steam and Methane

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 Symbols for Test Compressor Design Velocity Diagram Values

 Test Compressor Design Data (Rotor)

 Test Compressor Design Data (Stator)
NOMENCLATURE

A compressor flow area

A_p droplet project area

a acoustic speed

C_D drag coefficient

C_D_f drag coefficient corresponding to loss due to water film formed on blade surface

C_D_r drag coefficient corresponding to loss due to rough film surface of water on blade surface

C_w water vapor concentration

C_w_b water vapor concentration at droplet surface

c blade chord length

C_p specific heat at constant pressure

C_w specific heat of water

C_s humid heat for air-water mixture

D droplet diameter

D_d droplet diameter
$D_v$  diffusivity

$D_{eq}$  equivalent diffusion ratio

$D_{eq}^*$  equivalent diffusion ratio at minimum loss point

$d_{max}$  largest stable droplet diameter

$g_c$  Newton constant relating force and mass

$h_h$  heat transfer coefficient

$h_m$  mass transfer coefficient

$i$  incidence angle

$i^*$  incidence angle at minimum loss point

$J$  constant relating heat and work

$K_a$  thermal conductivity of air

$K_d$  thermal conductivity of gaseous film surrounding an evaporating droplet

$K_v$  thermal conductivity of water vapor

$k$  thermal conductivity

$k_g$  thermal conductivity of gaseous phase

$M$  absolute Mach number

$M_a$  assumed value of Mach number
Mr  relative Mach number

Mc  calculated value of Mach number

\( \dot{m} \)  mass flow rate

\( \dot{m}_{\text{film}} \)  mass flow rate of water film formed on blade surface

mw  molecular weight

N  rotor rotational speed

Nd  number of droplet

Nu  Nusselt number

\( P_{01} \)  total pressure at rotor inlet

\( P_{02} \)  total pressure at rotor outlet

\( P_{03} \)  total pressure at stator outlet

\( P_{01,r} \)  relative total pressure at rotor inlet

\( P_{02,r} \)  relative total pressure at rotor outlet

\( P_{02,ri} \)  ideal relative total pressure at rotor outlet

PR  pressure ratio

Pr  Prandtl number

\( P_{\text{ref}} \)  reference pressure

\( p_1 \)  static pressure at rotor inlet

\( p_2 \)  static pressure at rotor outlet
$p_3$ static pressure at stator outlet

$R$ gas constant

$Re$ Reynolds number

$r$ radius

$s$ pitch

$Sc$ Schmidt number

$Sh$ Sherwood number

$SN$ stability number

$T$ static temperature

$T_0$ total temperature

$T_{ref}$ reference temperature

$T_{01,r}$ relative total temperature at rotor inlet

$T_{02,r}$ relative total temperature at rotor outlet

$TR$ temperature ratio

$U_{tip}$ blade tip speed

$U$ blade speed

$V_z$ axial velocity
$V$ absolute velocity

$V_\theta$ tangential component of absolute velocity

$V_{\text{film}}$ velocity of film formed on blade surface

$W$ relative velocity

$W_\theta$ tangential component of relative velocity

$W_e$ Weber number

$x_g$ mass fraction of gas phase

$x_w$ mass fraction of liquid phase

**Greek Letters**

$\alpha$ absolute flow angle

$\beta$ relative flow angle

$\gamma$ specific heat ratio

$\eta$ adiabatic efficiency

$\Delta H_v$ latent heat of vaporization

$\Delta H_0$ rise in total enthalpy

$(\Delta H_0)_1$ work input to gaseous phase

$(\Delta H_0)_2$ work input absorbed by water droplets which do not impinge upon blade surface
\((\Delta H_0)_3\) work input absorbed by water droplets which impinge upon blade surface, adhere to form a film and are re-entrained from the trailing edge.

\((\Delta H_0)_4\) work input absorbed by droplets which impinge upon blade surface and rebound.

\(\Delta T_0\) rise in total temperature.

\(\Delta T_g\) rise in overall temperature of gaseous phase.

\((\Delta T_g)'_{ht}\) drop in temperature of gaseous phase due to heat transfer.

\((\Delta T_g)'_{wk}\) rise in temperature of gaseous phase due to work done.

\(\Delta T_w\) rise in overall temperature of droplet.

\((\Delta T_w)'_{ht}\) rise in temperature of droplet due to heat transfer.

\((\Delta T_w)'_{wk}\) rise in temperature of droplet due to work done.

\(\delta\) deviation angle.

\(\delta\) boundary layer displacement thickness.

\(\delta\) corrected pressure \((\delta=p/p_{ref})\).

\(\theta\) boundary layer momentum thickness.

\(\theta\) corrected temperature \((\theta=T/T_{ref})\).

\(\mu\) viscosity.

\(\rho\) density.
\( \sigma \) surface tension of droplet
\( \sigma \) solidity
\( \sigma_v \) particulate liquid volume fraction
\( \tau \) equivalent temperature ratio
\( \phi \) flow coefficient
\( \psi \) equivalent pressure ratio
\( \omega \) rotor angular velocity
\( \bar{\omega} \) total pressure loss coefficient
\( \bar{\omega}_{g,R} \) total pressure loss coefficient across rotor due to gas phase
\( \bar{\omega}_{g,S} \) total pressure loss coefficient across stator due to gas phase
\( \bar{\omega}_{\theta,R} \) total pressure loss coefficient due to the increase of momentum thickness because of the existence of small droplets in the boundary layer over a rotor blade surface
\( \bar{\omega}_{\theta,S} \) total pressure loss coefficient due to the increase of momentum thickness because of the existence of small droplets in the boundary layer over a stator blade surface
\( \bar{\omega}_{f,R} \) total pressure loss coefficient due to the momentum gained by thick water film moving over a rotor blade surface
\( \bar{\omega}_{f,S} \) total pressure loss coefficient due to the momentum gained by thick water film moving over a stator blade surface
\( \bar{\omega}_{r,R} \) total pressure loss coefficient due to turbulent flow of mixture over the rough film surface of rotor blade
$\omega_{r,S}$ total pressure loss coefficient due to turbulent flow of mixture over the rough film surface of stator blade

$\omega_{s,R}$ total pressure loss coefficient due to the Stokesian drag of droplets in rotor passage

$\omega_{s,S}$ total pressure loss coefficient due to the Stokesian drag of droplets in stator passage

Subscript

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<td>pertaining to design point</td>
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<td>g</td>
<td>pertaining to gas phase</td>
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<tr>
<td>i</td>
<td>pertaining to ideal process</td>
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<td>l</td>
<td>pertaining to liquid phase</td>
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<td>m</td>
<td>pertaining to mixture</td>
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<tr>
<td>r</td>
<td>pertaining to relative value with respect to rotor</td>
</tr>
<tr>
<td>ref</td>
<td>pertaining to reference value</td>
</tr>
<tr>
<td>R</td>
<td>pertaining to rotor</td>
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<tr>
<td>S</td>
<td>pertaining to stator</td>
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pertaining to water droplet

0 pertaining to stagnation value

1 pertaining to rotor inlet

2 pertaining to rotor outlet

3 pertaining to stator outlet

Superscript

* pertaining to minimum loss point

- pertaining to average value
SUMMARY

The PURDU-WICSTK program developed for predicting the performance of an axial flow compressor operating with mixtures of gases and water droplets has been described in detail. The utilization of the program has been illustrated with a test case.
CHAPTER I

INTRODUCTION

Water ingestion into an aircraft gas turbine arises due to two circumstantial reasons:

(1) wheel-generated spray clouds entering the engine inlet during take-off and landing from a rough runway with puddles of water; and

(2) rain, occasionally mixed with hail, entering the engine inlet during various parts of a flight in a rain storm.

A number of studies (Refs. 1-6) have shown that adverse effects can arise in engine performance due to such ingestion of water at engine inlet, when the engine has been designed for operation with air flow. In particular the engine may surge and may suffer blow-out or unsteadiness in the main burner or the after-burner. Simple corrective steps, such as resetting the throttle, have generally been ineffective in overcoming the problems of loss of power and nonsteady behaviour of the engine. In the case of wheel-spray ingestion, it has again become clear that basic changes in engine installation may be necessary in relation to inlets and landing wheels.

In the current investigation, there is no particular emphasis on the precise cause for the presence of water at the engine inlet. Water is assumed to enter the compressor along with air in droplet form. The droplet (nominal) diameters may be in the range of 20 to 1,300 microns. The water content by weight may be in the range of 2.5 to 15.0 per cent. In case of rain through which an aircraft may have to fly (Refs. 7-9) the droplet sizes may be of the order of 100 to 1,500 microns, although 3,000 micron size droplets have also been reported (Fig. 1.1). On the
other hand, 15.0 per cent of water by weight is probably to be considered as a large amount of ingestion into the inlet, corresponding to flight through storm conditions. Under such extreme conditions there may also be hail and snow ingestion into the engine. However, only water ingestion effects are examined here.

A comprehensive investigation of the problem of water ingestion into engines during flight should take into account details of the engine, its installation and the engine and aircraft controls. In the current investigation attention is focussed on the engine and its control.

Furthermore, it is felt that the response of the compressor in the engine to water ingestion plays a determining and crucial role in the response of the engine as a whole in view of two considerations.

1) The compressor receives the ingested water directly and, as a rotating machine, is most strongly affected by the ingested water, and also changes the "state of water" before the fluid enters the burner.

2) The compressor performance most directly affects the operating point of the engine under steady and transient state conditions.*

However, the compressor performance is affected by the presence of an inlet through the changes in the flow field introduced by it, especially the distortion of the compressor inlet flow field. While noting such strong interaction between the inlet and the compressor flow fields, the

* It may be pointed out that the operating point of an engine is determined by the matching between all of the components of the engine. Thus, the swallowing capacity of the turbine and nozzle, for example in a simple jet engine, at a given engine speed and turbine entry temperature, determine the engine operating point on the compressor map. However, any changes in the compressor outlet conditions affect the engine operating point most directly with a given turbine and nozzle. In particular, during water ingestion, the compressor map becomes completely changed, causing at least a change in the surge margin for a possible operating point and, in extreme cases, a total mismatch between the components. Even with a turbine and nozzle that have variable-area capability, it may become necessary to regulate the compressor outlet conditions independently.
most important aspect of the problem of water ingestion into an engine is still considered to be that pertaining to changes in the compressor performance itself.

In the case of turbofan engines, the air-water mixture upon entering the inlet becomes divided between the fan and the compressor. In particular cases, the compressor stream may have a different water content and droplet size distribution from that of the compressor stream in the absence of a fan. The effects of water ingestion are important both in the fan and the core engine compressor, although, perhaps, more so in the latter. When there is an after-burner in the fan stream or when a "mixing" Nozzle is employed, water ingestion into the fan stream may, however, become critically important.

From practical operational and design points of view, the effects of water ingestion in a compressor are as follows:

1. changes in temperature ratio, pressure ratio and efficiency of the compressor;
2. changes in surge line and operating line, and therefore the surge margin under given operating conditions;
3. blade deformation and erosion due to impact of droplets;
4. blade and casing deformation due to differential thermal expansion under transient conditions;
5. oscillation of pressure ratio and flow; and
6. changes in dynamic loading including aero-elastic effects.

For given entry conditions, the response of the compressor is determined by the following:

1. compressor geometry;
2. blade loading;
3. machine rotational speed; and
4. parameters of the engine of which the compressor is a part. The latter pertain to engine matching and should include not only the steady state performance parameters but also the mechanical, aero-dynamic and thermal inertia of the various components of the engine.
under transient conditions. It should be noted that in particular cases, the engine components may include a fan, an after-burner or a second nozzle as part of the engine.

In establishing the response of a compressor to water ingestion, it seems therefore useful to divide the total problem into two parts.

1. The compressor as a machine itself; and
2. The compressor as a part of the engine system.

In that fashion, one can separate the problems associated with engine matching (steady or transient) from those dependent upon the design of the compressor itself. Once the latter have been understood in detail, the engine as a whole may be studied from a system point of view. This is the approach adopted in the current investigation, since it is also especially convenient in conducting experimental studies.

A number of parameters pertaining to the air-water mixture entering a compressor during water ingestion are the following:

1. amount of water approaching and actually entering a blade row as a fraction of the total mass flow of fluid entering compressor;
2. form in which water is present, film and droplets;
3. temperature and pressure of air, temperature of water and temperature of machine;
4. vapor content;
5. turbulence; and
6. distortion, radial and circumferential.

Water vapor is always present in air-water mixtures ingested into an engine. The water vapor content changes in the compressor because of changes in pressure and temperature and because of transfer processes between the two phases. In particular, in a multi-stage compressor of large pressure ratio, there is a possibility of some of the water reaching local saturation temperature and undergoing a phase change due to boiling causing addition of large quantities of vapor to the gas phase.
It will be observed that each of the afore-mentioned six parameters changes after each blade row and the cumulative changes are therefore especially significant in a multi-stage machine. Furthermore, both time-dependent changes during sudden and sporadic ingestion, as well as steady state changes, as, for example, may arise in a laboratory experiment, need consideration. Thus, a detailed study of this problem should result in the determination and verification of methods for establishing (a) the changes in the performance of a compressor with water ingestion and (b) the changes in the state of fluid between the inlet and the outlet of the compressor. Such a study requires investigations both on a single row of blades (stationary and rotating) as well as on a unit with several rows of blades, under steady, transient, and distorted flow conditions. The latter is a means of establishing the response of a blade row to the flow generated by a preceding row. Furthermore, in order to examine the occurrence and effects of phase change in a blade row, the entry conditions to the blade row have to be selected such that they are suitable for such phase change. In a multi-stage compressor of large pressure ratio, there is, of course, a considerable change in air temperature at design conditions.

However, at this stage there are still considerable problems in conducting detailed measurements of two-phase flows in rotating machinery. It has therefore been felt in this investigation that one should aim at establishing overall performance changes and fluid flow changes in a compressor for given entry conditions of state of the two-phase fluid. Once such overall changes are established and related to verifiable models for performance prediction, it is felt one can proceed to more detailed measurements and modeling.

For a given compressor, the variables of interest during water ingestion are the following:

1. speed of the machine;
2. throttle setting;
3. stagnation pressure
4. temperature of air and water;
(5) amount of water as a fraction of total mixture flow;
(6) droplet size and number density distribution, and
(7) vapor content.
The variables (3) to (7) have a spanwise and circumferential distribution at compressor inlet, which may or may not be uniform.

The overall performance parameters of a compressor with two-phase flow are the following:
(1) pressure ratio temperature ratio and efficiency;
(2) changes in total water content and droplet size across the compressor; and
(3) changes in vapor content across the compressor.
Each of these varies along the span of a compressor blade. Both the measurements and prediction of these is beset with considerable difficulties at this time. In particular the determination of water and vapor content and of droplet size distribution requires further advances in instrumentation, data acquisition and data processing.

On establishing and demonstrating predictive methods for the estimation of such overall performance parameters for a compressor, an analysis can be carried out for an engine operating with water ingestion. Under steady conditions, the equilibrium running of a simple engine depends upon the following parameters:
(1) engine speed;
(2) mass flow;
(3) compressor performance with air-water mixture;
(4) ratio of turbine entry temperature to inlet temperature;
(5) turbine operational point (choked or unchoked); and
(6) thrust nozzle geometry.
Regarding the latter, a fixed geometry thrust nozzle with a constant area turbine restricts the number of variables for equilibrium running of a simple engine to a single parameter, namely engine speed or mass flow. In a variable geometry engine which permits changes in area of the turbine and the thrust nozzle, one can select, at least in principle, three variables independently for equilibrium running; engine speed, mass flow and turbine entry temperature.
An analysis of steady state equilibrium running of an engine with water ingestion can be expected to reveal the following:

1. whether equilibrium running is feasible under a given set of operating conditions,
2. changes in surge margin, and
3. effect of fuel scheduling and bleed of working fluid.

The latter, along with other aspects of engine operation, is dependent upon the type of engine control incorporated in the system.

Even when attention is focussed on the performance of a compressor by itself, several aspects of the performance may come to light only when it is operated as a part of an engine. However, if engine matching and its effect on compressor performance are not included, one can test a compressor as a separate unit by driving it, for example, with an aerodynamically-independent drive engine. This has been the basis for experimental studies in the current investigation.

1.1 Objectives and Scope of the Investigation

The principal objectives of the present investigation are as follows:

1. Establishment and demonstration of a predictive method for the calculation of the performance of an isolated compressor driven by an external drive unit and operating with air-water mixture flow; and
2. Obtaining and correlating experimental data on a multistage compressor with air-water mixture flow.

In both of the above, the vapor content of the mixture is taken into account, both initial humidity and changes in vapor content due to phase change of water droplets.

The other objectives of the present investigation are as follows:

1. Determination of the manner in which engine performance becomes affected by water droplet ingestion into the engine compressors; and
1.1.1 Analytical-Predictive Investigations

The analytical-predictive investigations are divided into two parts; (1) investigation on the performance of a compressor with water ingestion, and (2) analysis of a simple gas turbine engine with water ingestion.

Part I: Performance of Compressor with Water Ingestion

The analytical-predictive investigations on performance of compressor with water ingestion are divided into three parts:

1. Setting up the general aero-thermodynamic equations for compressor with air-water mixture flow and deduction of a one-dimensional model.

2. Establishing one-dimensional models for the estimation of performance of a compressor in four limiting cases as follows:
   (i) Ingestion of mixtures of gases directly into a compressor at inlet, without water droplets.
   (ii) Ingestion of small droplets that can be assumed to follow gas motion and hence absorb angular momentum.
   (iii) Ingestion of large droplets that can be assumed to move with equal probability in all directions and that cause a loss of compressor performance due to drag forces acting on them; and
   (iv) Injection of water with sudden phase change into steam at an appropriate stage in the compressor.

3. Adapting and exercising a three-dimensional streamline computer code, the UD-0300 computer code (Ref.10), for the case of direct ingestion of mixtures of gases into a compressor.

Part II: Analysis of Gas Turbine Engine with Water Ingestion

The objectives of Part II are as follows:
(1) Establishing a model for steady state engine matching with water ingestion; and
(2) Establishing a model for calculation of flight performance with water ingestion.

1.1.2. **Experimental Investigation**

The experimental investigations have been conducted on a specially built Test Compressor. The experimental investigations may be divided into the following three parts:

(1) Tests with air as the working fluid;
(2) Tests with air-methane mixture as the working fluid; and
(3) Tests with air-water droplet mixture as the working fluid.

The Air Force System Command has provided the Test Compressor and a T-63 Drive Engine for the experimental investigations. The predictive methods developed for estimating compressor performance with two phase flow have also been employed to calculate the performance of the Test Compressor.

Details regarding the Test Compressor and Drive Engine are provided in Appendix I to this Report.

The Test Compressor, it will be observed, has several limitations:

(1) the annulus and the blade heights are small and only overall performance parameters at one or at most two radial locations at the exit plane can be measured.

(2) the overall pressure and temperature ratios, even at design point, are too small to cause evaporation of more than 2.5 per cent of water (by weight) although the inlet temperature is raised to as high a value as 185°F (85°C).

(3) the compressor assembly permits little flexibility in locating instrumentation, especially at the compressor exit.

Since the Test Compressor casing has a plastic coating that does not
withstand high temperatures, the Test Compressor has been tested at low inlet temperatures in the range of 70°F to 100°F (about 20°C to 40°C). Such inlet temperatures do not cause water evaporation within the Test Compressor. The test program has therefore been conducted in two parts:

1. With a mixture of gases to simulate air-steam mixture flow corresponding to (a) high humidity in the air and (b) operation of different stages with air-steam mixture following complete evaporation of water, and
2. With air-water droplet mixture flow.

In examining the effects of presence of water vapor on a compressor performance, it is clear that another gas, such as methane, can be substituted for water vapor so long as the desired similarity laws with respect to Reynolds and Mach numbers, are satisfied. A comparison of properties for steam and methane is presented in Table 1.1. In view of the similar properties, experimental studies have been undertaken in this investigation utilizing air-methane mixtures.

The tests with air-water droplet mixtures have been conducted utilizing the following variables: mixture temperature, mixture composition and droplet size.

1.1.3 Measurements and Predictions

The results of the experimental investigation have been compared with prediction from models from the point of view of examining selected assumptions introduced in the models. It is clear that in view of limitations on the feasibility of measurements and the nature of assumptions introduced in modeling, comparison of analytical predictions with experimental results is restricted to certain overall performance parameters, in particular, the effects of mechanical-aero-thermodynamic interactions are established indirectly from overall compressor performance parameters and changes in water and vapor content.
<table>
<thead>
<tr>
<th></th>
<th>Steam</th>
<th>Methane</th>
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</thead>
<tbody>
<tr>
<td>Chemical Formula</td>
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<td>CH₄</td>
</tr>
<tr>
<td>Molecular Weight</td>
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<td>16.043</td>
</tr>
<tr>
<td>Specific Heat at Constant Pressure (Btu/lbm-°F)</td>
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<td>0.531*</td>
</tr>
<tr>
<td></td>
<td>(kJ/kg-°C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.863**</td>
<td>2.223*</td>
</tr>
<tr>
<td>Ratio of Specific Heats*</td>
<td>1.329**</td>
<td>1.304*</td>
</tr>
<tr>
<td>Enthalpy Increase</td>
<td>(Btu/lbm)</td>
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</tr>
<tr>
<td></td>
<td>62.70^</td>
<td>69.96^</td>
</tr>
<tr>
<td></td>
<td>(kJ/kg)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>145.84^</td>
<td>162.73^</td>
</tr>
</tbody>
</table>

*pressure = 1 atm; temperature = 78°F(26°C)

**pressure = 1 atm; temperature = 212°F (100°C)

^ pressure ratio, \( P_02/P_01 = 2.6 \); \( T_01 = 68°F (20°C) \)
1.1.4 Measurement Techniques

A brief review of instrumentation suitable for use in axial flow compressors and cascades operating with two phase fluid flow has been undertaken.

Two important overall performance parameters in compressors are the stagnation pressure ratio and the stagnation temperature ratio. A probe for the measurement of stagnation pressure in two phase flow has been developed. Its possible use in a compressor flow field has been examined. The development of a similar probe for the measurement of stagnation temperatures has been considered.

1.1.5 Engine Performance

The engines considered are those that have been designed for air flow through the inlet. Engines in which there may be injection of water at gas flow part locations beyond the compressor or in other stream such as fan ducts or after-burners are not under consideration. Specifically water ingestion effects have been examined in the case of simple turbo-jet and turbo-fan engines that have originally been designed for air flow operation only. Thus (a) the adverse flow effects due to water ingestion and (b) possible methods of mitigating such effects are of interest.

The response of an engine to water ingestion depends upon the following:
(a) component geometrical constraints;
(b) component performance characteristics; and
(c) nature of control incorporated into the engine.

The performance characteristics that are of major interest are the following:
(a) Changes in component performance characteristics due to water injection, in particular the compressor;
(b) Changes in operating characteristics of engine under conditions of equilibrium running;
(c) Changes in surge margin; and
(d) Limiting conditions of operation.

The foregoing have been analyzed in order to establish general performance trends without reference to specific engine configurations.

It may be noted that, because of the aero-thermo-mechanical processes arising on account of water ingestion, one may also expect, at least in extreme cases, aero-elastic processes becoming significant. However, the manner in which flutter, for example may be altered during two phase flow in compressors is not included for study in the current investigation.

1.2 Effects of Water Ingestion

The two critical factors during water ingestion may be said to be the following: (a) the aero-thermo-mechanical processes associated with two phase flow and (b) the centrifugal action on droplets in the compressor. The first of these includes droplet disintegration and evaporation processes. The latter gives rise to a change in gas phase mass flow as well as reduction in gas phase temperature. The centrifugal action introduces a radial distortion in the flow and fluid properties, and the distortion changes in every stage of a multistage compressor. In particular, the spanwise distribution of the composition and properties of the fluid, in terms of air, water vapor and water droplets (both content and size distribution), undergoes changes continuously along the compressor flow path. The effects (a) and (b) should be examined in a compressor in relation to the following:

(i) Formation of a water film in the tip region, that may flow into the diffuser;
(ii) Possibility of choking hub sections and stalling tip sections with redistributed gas and liquid phase mass flow; and
(iii) Nonuniform distribution of water vapor in the radial direction.

The foregoing will in turn affect engine performance depending
upon engine-matching and the type of control in the engine.

In order to reduce the effects of water ingestion, one can consider the following in order of increasing complexity.

(i) Bleeding of gas or liquid phase flow at appropriate locations in the compressor;
(ii) Resetting stator blades;
(iii) Modifying engine control; and
(iv) Introduction of variable geometry nozzle and also turbine.

The results of some preliminary studies on bleeding and also gas injection have been reported in Ref. 11.

1.2.1. Relation to Other Two-Phase Flow Problems in Turbo-Machinery

The current investigation deals with air-water droplet mixture ingestion into engines. On the other hand there has also been considerable interest in the problem of dust particle ingestion into engines (Refs. 12-13). In the latter case the principal interest is in erosion of blades and nozzles, although there is some loss in aerodynamic performance.

It is generally considered that the solid particulates may agglom-erate but not disintegrate during dust ingestion. Furthermore the heat and mass transfer processes between the two phases are considered negligible.

Solid particulates are also of interest in certain rocket motor nozzle and plume flows (Refs. 14-16). In this case, in addition to erosion and particulate drag effects it is generally necessary to take into account heat and mass transfer processes, as well as condensation, solidification and other phase change processes. However, in this case there is not strong centrifugal action, although there may be some swirl in the flow.

The low pressure stages of a steam turbine (Refs. 17-19) may
operate, as is well known, with steam-water droplet mixture, the droplets arising through condensation. However, in this case, while erosion, loss of aerodynamic performance, and consequences of strong centrifugal action are important, one does not have the problems of stalling and surging. A compressor is prone to surging and the surge margin with respect to operating line when it is part of an engine is an extremely important parameter in engine operation. Hence the problem of water ingestion into an engine compressor attains a level of complexity and significance much larger than the two phase flow problem in steam turbines. One should also note that a turbine is basically a nozzle, while a compressor flow (both past a blade and through a blade passage) involves diffusion and complicated blade wake interactions.

The current investigation does not take into account geometrical changes in a compressor because of, say, differential contraction of rotor and casing upon water ingestion. In general one can expect a change in clearance between rotor and stator. If a compressor has been designed with optimum clearance, one has to examine both aerodynamic and mechanical effects caused by changes in clearance. This aspect of water ingestion should be examined in relation to the general problems of gas flow path integrity (Ref. 20).

While nonsteady state operation is not considered in the current investigation, one of the most important aspects of water ingestion into compressors and engines is transient state operation. The aero-thermo-mechanical interactions including differential contraction of casing and rotor under transient conditions are significant in evolving various means of reducing the effects of water ingestion.

Finally, it is recognized that the entry conditions into a compressor are not uniform radially and circumferentially. The effects of distortion with respect to pressure, temperature, velocity and turbulence continue to be a subject of concern even with air flowing alone (Ref. 21). During water ingestion, one can expect, in general, distortion both at entry and to the compressor and at entry to each stage. The sensitivity
of an engine to water ingestion should include consideration of inlet distortion with regard to water content and water droplet size distribution. This problem has been entirely neglected in the current investigation. It may be pointed out that even under uniform inlet flow conditions, radial distortion, of course, arises within the compressor due to centrifuging and heat and mass transfer processes.

1.3 Implications of Models

The models derived in the current investigation may be divided into four groups:

(i) Model for the calculation of stage performance with air flow.
(ii) Model for droplet motion across a blade row.
(iii) Model for centrifuging of water, and
(iv) Model for heat and mass transfer processes, including droplet disintegration.

Experimental investigations have been conducted in order to determine overall compressor performance changes for given initial and operating conditions. A comparison between predictions and measurements therefore yields no detailed verification of the models. It is in any case doubtful if detailed verification of all aspects of the models can be obtained even if one attempted additional measurements.

The performance of a compressor stage with two phase flow depends upon the following parameters:

(i) geometrical design of blade and blade passage,
(ii) spacing between blade rows,
(iii) leading and trailing edge geometry,
(iv) casing geometry,
(v) rotor and stator blade junctions,
(vi) incoming flow conditions, and
(vii) operating speed and throttle setting

The foregoing determine (a) the stage work input, (b) the states
of gas and liquid phases, (c) the efficiency of compressor, (d) the redistribution of water and vapor and (e) limiting condition of steady state operation of compressor. When the compressor is part of an engine, the operating characteristics of all other components of the engine and of the engine as a whole are also determined by the compressor design and initial conditions. It is clear that while the models developed can be employed to determine the performance of any compressor under a set of reasonable operating conditions, there is need to establish relations that can be employed to scale the performance of a compressor with respect to design, initial and operating conditions. Such scaling laws have to be based on characteristic lengths, characteristic times, and blade, blade passage and blade row characteristics of the compressor and, when the compressor is part of an engine, the characteristics of other components such as diffuser, burner, turbine and nozzle. Under certain assumptions an attempt has been made to establish scaling laws for both a compressor and a simple jet engine.

1.4 Organization of Report

The final report is being issued in three parts:
   Part I: Analysis and Predictions
   Part II: Computational Programs; and
   Part III: Experimental Results and Discussion

This report constitutes Part II of the Final Report. Chapter I is the introduction. Chapter II is devoted to a discussion of overall program structure, and Chapter III presents a detailed description of the subroutines and external functions. The description of input data is given in Chapter IV while a description of the output is presented in Chapter V. Finally, a test case is discussed in Chapter VI.
CHAPTER II

OVERALL PROGRAM DESCRIPTION

The numerical-computational work undertaken in the current investigation may be divided into two parts as follows.

1. Modification of UD-0300 computer program for use with mixtures of gases; and
2. Development and use of PURDU-WICSTK program for the calculation of performance of axial compressors operating with air-water droplet mixture, based on one-dimensional flow analysis.

The modification of UD-0300 program for use with mixtures of gases is described in detail in Ref. 22. Typical performance results for the Test Compressor employed in this investigation, based on the UD-0300 program, are also presented in Ref. 22.

The PURDU-WICSTK program is described in the following.

2.1 Description of PURDU-WICSTK Program

The one-dimensional flow equations for two phase flow in axial compressors have been derived in detail and presented in Ref. 22. Those equations are suitable for the calculation of performance of any chosen section along the span of an axial compressor blade row. The PURDU-WICSTK is based on those equations. For given initial conditions at the entry to a stage, the outlet conditions can be calculated using those equations.

The PURDU-WICSTK deals with a fluid that may consist of (a) a mixture of three different gases and (b) a mixture of two types of water droplets, distinguished by size. The mixture of gases may consist of air, water vapor or steam, and methane. The water droplets may be "small" and
"large" diameter droplets. Small droplets are defined as those that follow the gas flow path and hence, absorb work input into the compressor along with the gaseous phase. Large droplets are assumed to move largely independently of the gas phase, with equal probability of motion in all directions and without absorbing work input but introducing drag losses. In the general two-phase mixture that is considered as the working fluid in the compressor, the proportion of the five constituents (namely, three gases and two types of droplets) may be chosen as desired in the initial conditions assumed for a calculation. Thus, to consider humid air carrying large droplets, the content of methane and of small droplets are set equal to zero while water vapor content is related to humidity.

The performance of a stage of a compressor is based in the PURDU-WICSTK Code on five physical models as follows.

1. Model for the calculation of stage performance with respect to the gaseous phase and water droplets.
2. Model for droplet motion across a blade row from a chosen upstream location to a designated downstream location.
3. Model for centrifuging of water droplets.
4. Model for heat and mass transfer processes between the two phases; and
5. Model for droplet break-up and equilibration with respect to size.

The foregoing five models have been described in detail in Ref. 22. However, a further description is included in Appendix 2 of this report regarding the model for the calculation of stage performance with respect to gaseous phase and water droplets.

The general procedure for calculation is the same as described in Ref. 22. The performance of a stage is calculated for given initial and operating conditions with respect to the gaseous phase and the water droplets. Regarding small droplets, any fraction of their total number may be taken into account depending upon assumptions relating to droplet impingement and rebound processes. Details are provided in Ref. 22. Then, at the exit of a blade row, the three major processes, namely
(1) centrifugal action on droplets, (2) heat and mass transfer processes between the two phases and (3) droplet size adjustment, are taken into account. When the stage performance parameters are corrected for the afore-mentioned three processes then one obtains the outlet conditions from a stage.

The outlet conditions from a stage are modified, to account for geometry of compressor, in order to obtain the initial conditions for the next stage, where such exists.

Calculations are repeated for subsequent stages based on the well-known concept of stage-stacking.

The Code can be used to predict the design point performance as well as off-design performance of a multi-stage compressor. Regarding off-design performance calculation, further details are provided in Appendix 2 of this report.

The Code is also suitable for the calculation of compressor performance with (a) bleeding of working fluid at different stages in the compressor and (b) resetting stator blades. It may be recalled that two of the recommended methods for mitigating the effects of water ingestion in compressors consist in (a) bleeding of working fluid and (b) resetting of stator blades.

The program is written for calculation of performance both in British and metric units.

2.2 Main Program

The program consists of a main program, twenty seven subroutines and thirteen external functions.

The main computer code routine is entitled MAIN. It calls all of the major subroutines in the code. MAIN first reads all of the input data and prints them out. Then MAIN calls the subroutine WICSPD to calculate the design point performance.
At the compressor inlet the overall mixture mass flow rate is determined from the inputed initial overall flow coefficient and selected compressor operating speed. In order to calculate the stage performance, it is necessary to establish the stage axial velocity and stage flow coefficient at the entry to the stage. The axial velocity and therefore the stage flow coefficient are determined by the composition of the mixture. The influence of mixture composition arises through (a) the density of the mixture and (b) the proportion of large droplets in the mixture, the large droplets, it may be recalled, having random motion with respect to the gas phase and the small droplets. Details regarding stage flow coefficient are provided in Ref. 22 and Appendix 2 of this report.

2.2.1 Work Done in Stage

The stage performance calculation may be carried out in one of three ways by setting the input parameter IPERFM equal to 1, 2, or 3: (1) WICSPA is called to utilize inputed stage characteristics; (2) WICSPB is called to utilize the analytical/correlation method (Appendix 2) for small droplets; and (3) WICSPC is called to utilize method described in Appendix 2 for large (or general) droplets. The program is written such that if more than 20 per cent of droplets belong to the class of large droplets, WICSPC is always used.

The foregoing stage performance calculation refers only to the determination of work done by the stage on the fluid that is assumed to absorb work input into the stage. The state of the fluid at the exit of the stage is then obtained by accounting for (1) the centrifugal action on droplets leading to a redistribution of liquid phase, (2) heat and mass transfer processes leading to a redetermination of mass flow and temperature of both gas phase and liquid phase.

2.2.2 Droplet Impingement Processes

In order to perform calculations pertaining to impingement of droplets on rotor blades and rebound of droplets, MAIN calls subroutine WICIRS and WICIRL for small and large droplets, respectively. The small and large droplet trajectories are different by assumption and their impingement on blades, therefore, has to be calculated in different ways. For stator blade, the subroutines WICISSL and WICISL are called for small and large droplets, respectively.
The rebound of droplets is treated parametrically as a fraction of the droplets that impact a blade. The unrebound droplets are assumed to move over the blade surface and to be reingested into the blade wake at the blade trailing edge. Details regarding these processes may be found in Ref. 22.

2.2.3 Droplet Drag

The stage performance calculation described earlier yields a value of gas phase pressure at the stage exit. This to be corrected for droplet drag in the case of large droplets. The droplet drag due to large droplets is accounted for by calling the subroutine WICDRG. The pressure loss due to drag depends upon (a) the chosen drag coefficient, and (b) the number of droplets taken into consideration. The latter in turn depends upon the droplet impingement and rebound processes. Further details may be found in Ref. 22.

2.2.4 Droplet Size Adjustment

At the trailing edge of a blade, it is necessary to establish (a) the size of droplets that re-entrained into a blade surface and (b) the nominal size of all of the droplets. In both cases, the droplet size is assumed to be determined by the critical value of Weber number. The subroutine WICWAK yields the size of droplets that are re-entrained. Regarding the nominal size of all of the droplets in the blade wake region, the WICSIZ is called to determine it. It may be observed that the droplets attain an equilibrium size in the blade wake region only after traversing a distance since the droplets undergo an accelerating motion starting from the blade trailing edge till they attain momentum equilibrium with respect to the gas phase.

2.2.5 Centrifugal Action

The spanwise redistribution of droplets due to centrifugal action is based on the theory developed in Ref. 22. The centrifugal action arises due to (a) the whirl component of velocity of droplets and (b) the rota-
tional motion of blades in a rotor. In the case of small droplets, centrifugal action thus applies to (i) droplets in blade passages with respect to the whirl component of velocity and (ii) droplets on blade surfaces with respect to the blade rotational velocity. In the case of large droplets, on the other hand, centrifugal action arises only for droplets that impact the blade and are not rebound; in other words, for droplets that impinge on a blade and remain on it.

The centrifugal action arises both in a stator and a rotor for small droplets, while it arises only in a rotor for large droplets. This is again based on the earlier postulated difference between small and large droplet motion.

The centrifugal action is determined utilizing the subroutine WICCEN.

It may be pointed out that the spanwise redistribution of droplets due to centrifugal action is a time-dependent process. In other words, the total effect of centrifugal force is proportional to the length of time over which the force acts. It is assumed in the model adopted here that the time over which centrifugal force action arises on a droplet during its passage through a blade row is the mean length of time required for transit through the blade row. Thus, the particles at the trailing edge of a blade row, as they come out of a blade row, are assumed to be centrifuged at that location over a period of time equal to the time of passage through the blade row under consideration. A similar assumption applies if a complete stage is being considered. Further details are available in Ref. 22.

2.2.6. Heat and Mass Transfer Processes

The heat and mass transfer processes between the two phases are also time-dependent processes. The mean duration of time for heat and mass transfer processes across a blade row or a stage is again calculated on the basis of mean transit time through a blade row or a stage. The heat transfer is from the gas phase to the liquid phase. The mass transfer arises due to two reasons as follows.
(i) The change of pressure and temperature in a stage and the resulting change in thermodynamic equilibrium conditions and,
(ii) the evaporation of water when conditions are appropriate.
The details of models for heat and mass transfer calculations are presented in Ref. 22.

The heat and mass transfer calculations are carried out by calling the subroutines WICHET and WICMAS, respectively, at the exit of a stage.

The stage exit conditions are thus fully established and are printed out.

2.2.7. Multi-Stage Compressor Performance

When there is a stage following the stage for which exit conditions have been determined, the inlet conditions to the following stage are determined taking into account changes in the geometry of the interstage spacing. Utilizing those conditions as the input conditions, the performance of the following stage is established in terms of final exit conditions from that stage. The procedure is the same as that described for the first stage.

This procedure is continued for all of the stages in the case of a multi-stage compressor and the exit conditions from the last stage are printed out as the output conditions of the compressor for given initial conditions into the first stage of the compressor at the chosen operating speed.

2.3 Off-Design Performance

In order to calculate the performance of a stage at an off-design point, with respect to speed and/or mass flow, one utilizes the subroutine WICSPA, WICSPB, or WICSPC by setting the input parameter IPERFM = 1, 2, or 3. The utilization of the three subroutines is the same as at the design point.
It may be pointed out that the profile loss calculation procedure set out in the subroutine WICGSL is considered especially suitable for the case of the Test Compressor employed in the current investigation. In another case, appropriate modifications or even a replacement of this procedure may become necessary.

### 2.3.1. Corrections at Stage Exit

In Section 2.2, the methods of applying corrections to the basic stage performance with respect to the following have been discussed.

1. droplet impingement processes,
2. droplet drag loss,
3. droplet size adjustment,
4. centrifugal action, and
5. heat and mass transfer process.

It may be recalled that the corrections are related to (a) the assumed distinctions between small and large droplets, and (b) the parametrization of droplet impingement, rebound and reingestion.

In performing off-design performance calculations, the procedure is the same as described in Section 2.2. The distinctions between small and large droplets remain the same. One can, of course, introduce desired values for droplet impingement, rebound and reingestion at each calculation point.

### 2.4 Bleeding and Injection

At the exit of any stage of a compressor, the output yields the composition of the mixture of gases and liquid droplets. In establishing inlet conditions into the following stage, in addition to taking into account changes due to the geometry of inter-stage spacing, one can take into account bleeding or injection of any component of the mixture by adjusting the mass flow and the mixture ratios.
2.5 **Stator Blade Setting**

The program includes a provision for blade setting as feature of off-design performance calculations. Further details are provided in Appendix 2.

2.6 **Calculation of Stage Losses**

The calculation of stage losses is fully described in Appendix 2. A summary is provided here.

The stage loss calculation consists of the following five subroutines:

1. Subroutine WICGSL
   single-phase (gas) flow profile loss calculated using the analytical/correlation method;

2. Subroutine WICSDL
   loss for small droplets on account of the change in momentum thickness of boundary layer due to the presence of such droplets;

3. Subroutine WICSTL
   loss due to Stokesian drag of droplets in the free stream of blade passage;

4. Subroutine WICFML
   loss due to film formed on blades when large droplets are present either by themselves or along with small droplets; and

5. Subroutine WICRSL
   loss due to the mixture boundary layer formed over the rough film surface referred to in (4).

The calculation schemes for various types of working fluids are as follows.

(a) In dealing with the flow of gas phase along, two options exist as follows.

   1. Using inputed stage characteristics by utilizing subroutine WICSPA; or
   2. Using analytical/correlation method by utilizing the relevant part of subroutine WICSPB and WICGSL.
In dealing with the flow of a mixture of gas and small droplets, again two options exist as follows.

1. Using inputed stage characteristics through the use of WICSPA and correct for the pressure of droplets by using the subroutine WICSDL; or

2. Using analytical/computational method according to subroutines WICSPB, WICGSL, and WICSDL.

Finally, in dealing with the flow of a mixture of gas and large or large and small droplets, one proceeds by using the subroutines WICSPC, WICGSL, WICSTL, WICFML, and WICRSL.

2.7 Overall Program Structure

The overall program structure is presented in Fig. 2.1 and also described below step by step.

Step 1: Read input data.
Step 2: Printout inputed data.
Step 3: Calculate the design point performance by calling WICSPD.
Step 4: Read initial flow coefficient.
Step 5: Calculate mass flow rate of gas phase and liquid phase from the inputed initial flow coefficient. The subroutine WICPRP and WICMAS are called.
Step 6: Calculate stage performance in one of the following five cases:
   (i) If there is no liquid phase, and the inputed stage characteristic curves are to be used, WICSPA is called.
   (ii) If there is no liquid phase, and analytical/correlation method is to be used, WICSPB is called.
   (iii) If more than 80 per cent of droplets belongs to "small" droplet, and the inputed stage characteristic curves are to be used, WICSPA is called.
   (iv) If more than 80 per cent of droplets belongs to "small" droplet and the analytical/correlation method is to be used, WICSPB is called.
(v) If more than 20 per cent of droplet belongs to "large" droplet, WICSPC is called.

Step 7: Calculation of droplet impingement on rotor blade:
For small droplets, WICIRS is called.
For large droplets, WICIRL is called.

Step 8: Droplet size adjustment at rotor outlet: WICWAK and WICSIZ are called.

Step 9: Calculation of centrifugal action and spanwise redistribution of droplets:
For small droplet, WICCEN and WICDMS are called.
For large droplet, WICCEN and WICDML are called.

Step 10: Calculation of droplet impingement on stator blade:
For small droplet, WICISS is called.
For large droplet, WICISL is called.

Step 11: Droplet size adjustment at stator outlet: WICWAK AND WICSIZ are called.

Step 12: Calculation of heat transfer:
WICHET is called.

Step 13: Calculation of mass transfer:
WICMAS is called.

Step 14: Printout stage performance.

Step 15: Repeat steps (6) ~ (14) until the complete stage performance is obtained.

Step 16: Calculate the overall performance and print them out.

Step 17: Repeat steps (4) ~ (16) for a new value of initial flow coefficient.
CHAPTER III

SUBROUTINES AND EXTERNAL FUNCTIONS

There are 27 subroutines and 13 external functions in this program. The following is the list of subroutines and external functions. Only brief descriptions of these subprograms are given here. A more detailed description of each subprogram is presented in Appendix 3.

Subroutine WICSPA: calculation of stage performance based on the imputed stage characteristic curves.
Subroutine WICSPB: calculation of stage performance based on the analytical/correlation method for small droplet.
Subroutine WICSPC: calculation of stage performance based on the analytical/correlation method for large droplet.
Subroutine WICSPD: calculation of design point performance.
Subroutine WICSCC: calculation of the equivalent pressure ratio, equivalent pressure ratio, equivalent temperature rise ratio, and stage adiabatic efficiency for a particular stage based on the imputed stage characteristic curves.
Subroutine WICGSL: calculation of single-phase (gas) flow loss.
Subroutine WICSDL: calculation of loss for small droplets on account of the change in momentum thickness of boundary layer due to the presence of such droplets.
Subroutine WICSTL: calculation of loss due to Stokesian drag of droplets in the free stream of blade passage.
Subroutine WICFML: calculation of loss due to film formed on blade surface when large droplets are present either by themselves or along with small droplets.
Subroutine WICRSL: calculation of loss due to the rough surface when large droplets are present either by themselves or along with
Subroutine WICVT: calculation of components of velocity triangle and angles.
Subroutine WICCEN: calculation of swanwise replacement of droplets due to centrifugal action.
Subroutine WICDMS: calculation of amount of small droplets which is centrifuged.
Subroutine WICDML: calculation of amount of large droplets which is centrifuged.
Subroutine WICDRG: calculation of drag force on droplet.
Subroutine WICMAC: calculation of Mach number.
Function WICASD: calculation of acoustics speed in two phase flow.
Subroutine WICBOA: calculation of blade outlet angle.
Subroutine WICEDD: calculation of equivalent diffusion at design point.
Function WICED: calculation of equivalent diffusion.
Function WICMTK: calculation of dimensionless momentum thickness.
Function WICLOS: calculation of total pressure loss coefficient.
Subroutine WICIRS: calculation of droplet impingement and rebound in rotor for small droplet.
Subroutine WICIRL: calculation of droplet impingement and rebound in rotor for large droplet.
Subroutine WICISS: calculation of droplet impingement and rebound in stator for small droplet.
Subroutine WICISL: calculation of droplet impingement and rebound in stator for large droplet.
Subroutine WICWAK: Calculation of water reingestion into wake.
Subroutine WICHET: calculation of heat transfer between gaseous phase and droplets.
Subroutine WICMAS: calculation of mass transfer between gaseous phase and droplets.
Function WICMTR: calculation of mass transfer rate.
Function WICPWB: calculation of vapor pressure.
Function WICNEW: calculation of new trial value in the iterative procedure.
Function WICTAN: calculation of the value of tangent function.
Function WICBPT: calculation of boiling point.
Function WICSH: calculation of specific humidity.
Subroutine WICSIZ: calculation of nominal droplet size.
Subroutine WICPRP: calculation of flow properties for gaseous phase.
Function WICCRA: calculation of specific heat at constant pressure for air.
Function WICCPH: calculation of specific heat at constant pressure for vapor.
Function WICCPC: calculation of specific heat at constant pressure for methane.
CHAPTER IV
INPUT DATA

All input data that are needed to use PURDU-WICSTK computer code are described in this section. The input data are presented in the same sequence as they are used in the program. The units for the input data can be selected as either all Metric or all English by choosing the value of IUNIT as shown in Table 4.1.

The following is a list of the input data as they are read in MAIN. Figures 4.1 and 4.2 show the geometry of compressor stage and angles associated with a typical rotor blade element.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Input Data</th>
<th>Comment</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NS</td>
<td>number of stage</td>
<td>I1</td>
</tr>
<tr>
<td>2</td>
<td>RRHUB(I)</td>
<td>hub radius at Ith stage rotor inlet. I = 1 \sim NS Unit: inch or cm</td>
<td>F5.3</td>
</tr>
<tr>
<td>3</td>
<td>RC(I)</td>
<td>chord length of Ith stage rotor I = 1 \sim NS Unit: inch or cm</td>
<td>F5.3</td>
</tr>
<tr>
<td>4</td>
<td>RBLADE(I)</td>
<td>number of blade for Ith stage rotor. I = 1 \sim NS</td>
<td>F5.2</td>
</tr>
<tr>
<td>5</td>
<td>STAGER(I)</td>
<td>stager angle for Ith stage rotor I = 1 \sim NS Unit: degree</td>
<td>F5.2</td>
</tr>
<tr>
<td>6</td>
<td>SRHUB(I)</td>
<td>hub radius at Ith stage stator inlet. I = 1 \sim NS, I = NS+1 for IGV Unit: inch or cm</td>
<td>F5.3</td>
</tr>
<tr>
<td>7</td>
<td>SC(I)</td>
<td>chord length of Ith stage stator I = 1 \sim NS, I=NS+1 for IGV Unit: inch or cm</td>
<td>F5.3</td>
</tr>
</tbody>
</table>
TABLE 4.1 INDEX FOR UNIT SELECTION

<table>
<thead>
<tr>
<th>UNIT</th>
<th>Unit of Input data</th>
<th>Unit of Output Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>English</td>
<td>English</td>
</tr>
<tr>
<td>2</td>
<td>Metric</td>
<td>Metric</td>
</tr>
<tr>
<td>3</td>
<td>English</td>
<td>Metric</td>
</tr>
<tr>
<td>4</td>
<td>Metric</td>
<td>English</td>
</tr>
<tr>
<td>Card No.</td>
<td>Input Data</td>
<td>Comment</td>
</tr>
<tr>
<td>----------</td>
<td>------------</td>
<td>---------</td>
</tr>
<tr>
<td>8</td>
<td>SBLADE(I)</td>
<td>number of blade for Ith stage stator. I=1~NS, I=NS+1 for IGV</td>
</tr>
<tr>
<td>9</td>
<td>SIGUMR(I)</td>
<td>solidity of Ith stage rotor I = 1~ NS</td>
</tr>
<tr>
<td>10</td>
<td>SIGUMS(I)</td>
<td>solidity of Ith stage stator I=1~NS, I=NS+1 for IGV</td>
</tr>
<tr>
<td>11</td>
<td>FNF</td>
<td>fraction of design corrected rotor speed for a particular speed</td>
</tr>
<tr>
<td>12</td>
<td>XDIN</td>
<td>initial water content (mass fraction) of small droplet</td>
</tr>
<tr>
<td>12</td>
<td>ICENT</td>
<td>index for centrifugal calculation of small droplet ICENT = 1 when XDIN = 0.0 otherwise ICENT = 2</td>
</tr>
<tr>
<td>12</td>
<td>XDDIN</td>
<td>initial water content (mass fraction) of large droplet</td>
</tr>
<tr>
<td>12</td>
<td>IICNET</td>
<td>index for centrifugal calculation of large droplet IICENT=1 when XDDIN=0.0 otherwise IICENT = 2</td>
</tr>
<tr>
<td>13</td>
<td>TOG</td>
<td>total temperature of gas phase at compressor inlet Unit: Rankin or Kelvin</td>
</tr>
<tr>
<td>13</td>
<td>TOW</td>
<td>temperature of droplet at compressor inlet Unit: Rankin or Kelvin</td>
</tr>
<tr>
<td>13</td>
<td>PO</td>
<td>total pressure at compressor inlet Unit: lbf/ft$^2$ or N/m$^2$</td>
</tr>
<tr>
<td>14</td>
<td>DIN</td>
<td>initial diameter of small droplet Unit: μm</td>
</tr>
<tr>
<td>14</td>
<td>DDIN</td>
<td>initial diameter of large droplet Unit: μm</td>
</tr>
<tr>
<td>Card No.</td>
<td>Input Data</td>
<td>Comment</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
<td>---------</td>
</tr>
<tr>
<td>15</td>
<td>FND</td>
<td>rotor corrected speed at design point</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit: RPM</td>
</tr>
<tr>
<td>15</td>
<td>TO1D</td>
<td>compressor inlet temperature at design point</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit: Rankin or Kelvin</td>
</tr>
<tr>
<td>15</td>
<td>PO1D</td>
<td>compressor inlet pressure at design point</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit: lbf/ft² or N/m²</td>
</tr>
<tr>
<td>16</td>
<td>XCH4</td>
<td>initial methane content (mass fraction)</td>
</tr>
<tr>
<td>16</td>
<td>RHUMID</td>
<td>initial relative humidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit: per cent</td>
</tr>
<tr>
<td>17</td>
<td>FMWA</td>
<td>molecular weight of air</td>
</tr>
<tr>
<td>17</td>
<td>FMWV</td>
<td>molecular weight of steam</td>
</tr>
<tr>
<td>17</td>
<td>FMWC</td>
<td>molecular weight of methane</td>
</tr>
<tr>
<td>18</td>
<td>PREB</td>
<td>percent of water droplet that rebound after impingement on blade surface</td>
</tr>
<tr>
<td>18</td>
<td>DLIMIT</td>
<td>maximum diameter for small droplet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit: μm</td>
</tr>
<tr>
<td>19</td>
<td>STAGES(I)</td>
<td>stager angle for Ith stage stator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I=1~NS, I=NS+1 for IGV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit: degree</td>
</tr>
<tr>
<td>20</td>
<td>GAPR(I)</td>
<td>gap between Ith stage rotor and (I-1)th stage stator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I = 1~NS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit: inch or cm</td>
</tr>
<tr>
<td>21</td>
<td>GAPS(I)</td>
<td>gap between rotor blade and stator blade for Ith stage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I = 1~NS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit: inch or cm</td>
</tr>
<tr>
<td>Card No.</td>
<td>Input Data</td>
<td>Comment</td>
</tr>
<tr>
<td>----------</td>
<td>------------</td>
<td>---------</td>
</tr>
</tbody>
</table>
| 22       | RRTIP(I)   | blade tip radius at Ith stage rotor inlet<br>
|          |            | I = 1 ~NS<br>
|          |            | Unit: inch or cm | F 6.3 |
| 23       | SRTIP(I)   | blade tip radius at Ith stage stator inlet<br>
|          |            | I = 1 ~NS<br>
|          |            | Unit: inch or cm | F 6.3 |
| 24       | IPERFM     | index for stage performance calculation<br>
|          |            | IPERFM=1: subroutine WICSPA is used<br>
|          |            | IPERFM=2: subroutine WICSPA is used<br>
|          |            | IPERFM=3: subroutine WICSPA is used | I1 |
| 24       | IUNIT      | index for unit<br>
|          |            | IUNIT=1: Input=English, Output=English<br>
|          |            | IUNIT=2: Input=Metric, Output=Metric<br>
|          |            | IUNIT=3: Input=English, Output=Metric<br>
|          |            | IUNIT=4: Input=Metric, Output=English | I1 |
| 25       | IRAD       | index for radius at which calculation is carried out<br>
|          |            | IRAD = 1: performance at tip<br>
|          |            | IRAD = 2: performance at mean<br>
|          |            | IRAD = 3: performance at hub | I1 |
| 26       | RT(I)      | rotor inlet radius at which tip performance calculation is carried out<br>
|          |            | I = 1 ~NS<br>
|          |            | Unit: inch or cm | F 5.3 |
| 27       | RM(I)      | rotor inlet radius at which mean line performance calculation is carried out<br>
|          |            | I = 1 ~NS<br>
|          |            | Unit: inch or cm | F 5.3 |
| 28       | RH(I)      | rotor inlet radius at which hub performance calculation is carried out<br>
|          |            | I = 1 ~NS<br>
|          |            | Unit: inch or cm | F 5.3 |
| 29       | ST(I)      | stator inlet radius at which tip performance calculation is carried out<br>
|          |            | I = 1 ~NS<br>
<p>|          |            | Unit: inch or cm | F 5.3 |</p>
<table>
<thead>
<tr>
<th>Card No.</th>
<th>Input Data</th>
<th>Comment</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>SM(I)</td>
<td>stator inlet radius at which mean line performance is carried out ( I = 1 \sim NS ) ( \text{Unit: inch or cm} )</td>
<td>F 5.3</td>
</tr>
<tr>
<td>31</td>
<td>SH(I)</td>
<td>stator inlet radius at which hub performance calculation is carried out ( I = 1 \sim NS ) ( \text{Unit: inch or cm} )</td>
<td>F 5.3</td>
</tr>
<tr>
<td>32</td>
<td>BLOCK(I)</td>
<td>blockage factor for ( \text{Ith stage rotor} ) ( 0 &lt; \text{BLOCK(I)} &lt; 1 )</td>
<td>F 5.3</td>
</tr>
<tr>
<td>33</td>
<td>BLOCKS(I)</td>
<td>blockage factor for ( \text{Ith stage stator} ) ( 0 &lt; \text{BLOCKS(I)} &lt; 1 )</td>
<td>F 5.3</td>
</tr>
<tr>
<td>34</td>
<td>BET1MR(I)</td>
<td>blade metal angle at ( \text{Ith stage rotor inlet} ) ( \text{Unit: degree} )</td>
<td>F 5.2</td>
</tr>
<tr>
<td>35</td>
<td>BET2MR(I)</td>
<td>blade metal angle at ( \text{Ith stage rotor outlet} ) ( \text{Unit: degree} )</td>
<td>F 5.2</td>
</tr>
<tr>
<td>36</td>
<td>BET1MS(I)</td>
<td>blade metal angle at ( \text{Ith stage stator inlet} ) ( \text{Unit: degree} )</td>
<td>F 5.2</td>
</tr>
<tr>
<td>37</td>
<td>BET2MS(I)</td>
<td>blade metal angle at ( \text{Ith stage stator outlet} ) ( \text{Unit: degree} )</td>
<td>F 5.2</td>
</tr>
<tr>
<td>38</td>
<td>DMASS</td>
<td>mass flow rate at design point ( \text{Unit: lb}/\text{s or kg}/\text{s} )</td>
<td>F 10.6</td>
</tr>
<tr>
<td>39</td>
<td>PR12D(I)</td>
<td>total pressure ratio for the ( \text{Ith stage rotor at design point}; I = 1 \sim NS )</td>
<td>F 5.3</td>
</tr>
<tr>
<td>40</td>
<td>PR13D(I)</td>
<td>total pressure ratio for ( \text{Ith stage at design point}; I = 1 \sim NS )</td>
<td>F 5.3</td>
</tr>
<tr>
<td>Card No.</td>
<td>Input Data</td>
<td>Comment</td>
<td>Format</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
<td>---------</td>
<td>--------</td>
</tr>
<tr>
<td>41</td>
<td>ETARD(I)</td>
<td>adiabatic efficiency for Ith stage rotor</td>
<td>F 5.3</td>
</tr>
<tr>
<td>42</td>
<td>SAREA(I)</td>
<td>stream tube area Ith stage rotor inlet Unit: ft² or m²</td>
<td>F 10.7</td>
</tr>
<tr>
<td>43</td>
<td>SAREAS(I)</td>
<td>stream tube area for Ith stage stator inlet Unit: ft² or m²</td>
<td>F 10.7</td>
</tr>
<tr>
<td>44</td>
<td>DELB1R(I)</td>
<td>change of blade metal angle for Ith stage rotor resetting ( I = 1 \sim NS ) Unit: degree</td>
<td>F 5.2</td>
</tr>
<tr>
<td>45</td>
<td>DELB1S(I)</td>
<td>change of blade metal angle for Ith stage stator resetting ( I = NS, I = NS + 1 ) for IGV</td>
<td>F 5.2</td>
</tr>
<tr>
<td>46</td>
<td>XG1BLD(I)</td>
<td>amount of bleed or injection of air at Ith stage outlet ( I = 1 \sim NS ) ( XG1BLD(I) &lt; 0 ) for bleed ( XG1BLD(I) = 0 ) for no bleed or injection ( XG1BLD(I) &gt; 0 ) for injection</td>
<td>F 5.3</td>
</tr>
<tr>
<td>47</td>
<td>XG2BLD(I)</td>
<td>amount of bleed or injection of steam at Ith stage outlet ( I = 1 \sim NS ) ( XG2BLD(I) &lt; 0 ) for bleed ( XG2BLD(I) = 0 ) for no bleed or injection ( XG2BLD(I) &gt; 0 ) for injection</td>
<td>F 5.3</td>
</tr>
<tr>
<td>48</td>
<td>XG3BLD(I)</td>
<td>amount of bleed or injection of methane at Ith stage outlet ( I = 1 \sim NS ) ( XG3BLD(I) &lt; 0 ) for bleed ( XG3BLD(I) = 0 ) for no bleed or injection ( XG3BLD(I) &gt; 0 ) for injection</td>
<td>F 5.3</td>
</tr>
<tr>
<td>Card No.</td>
<td>Input Data</td>
<td>Comment</td>
<td>Format</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
<td>---------</td>
<td>--------</td>
</tr>
<tr>
<td>49</td>
<td>XWBLD(I)</td>
<td>amount of bleed or injection of small droplet at Ith stage outlet $I = 1 \sim NS$ XWBLD(I) &lt; 0 for bleed XWBLD(I) = 0 for no bleed or injection XWBLD(I) &gt; 0 for injection</td>
<td>F 5.3</td>
</tr>
<tr>
<td>50</td>
<td>XWWBLD(I)</td>
<td>amount of bleed or injection of large droplet at Ith stage outlet $I = 1 \sim NS$ XWWBLD(I) &lt; 0 for bleed XWWBLD(I) = 0 for no bleed or injection XWWBLD(I) &gt; 0 for injection</td>
<td>F 5.3</td>
</tr>
<tr>
<td>51</td>
<td>BET2SS(I)</td>
<td>absolute flow angle at Ith stage stator outlet $I = 1 \sim NS$, I=NS1 for IGV</td>
<td>F 5.2</td>
</tr>
<tr>
<td>52</td>
<td>FAI</td>
<td>initial flow coefficient. The user can input FAI as many as one wants. However, one card must contain only one FAI and the last card must be 9.99999</td>
<td>F 7.5</td>
</tr>
</tbody>
</table>
CHAPTER V

OUTPUT

The user can select the units for output variables by choosing the value of the input variable IUNIT as shown in Table 4.1.

There are two kinds of output in this program code--regular output and diagnostic output. The regular output consists of four parts as follows:

1. output of the inputed data;
2. output of design point performance;
3. output of stage performance; and
4. output of overall performance.

5.1 Output of Inputed Data

All of the data inputed can be printed out at the beginning of output.

5.2 Output of Design Point Performance

5.2.1 Compressor Inlet (Design Point Performance)

At the compressor inlet, the following properties can be printed out for the design point performance:

1. total temperature at compressor inlet: (R) or (K)
2. total pressure at compressor inlet: (lbf/ft$^2$) or (N/m$^2$)
3. static temperature at compressor inlet: (R) or (K)
4. static pressure at compressor inlet: (lbf/ft$^2$) or (N/m$^2$)
5. static density at compressor inlet: (lbm/ft$^3$) or (kg/m$^3$)
6. acoustic speed at compressor inlet: (ft/s) or (m/s)
7. axial velocity at compressor inlet: (ft/s) or (m/s)
8. Mach number at compressor inlet
9. stream tube area at compressor inlet: (ft$^2$) or (m$^2$)
10. flow coefficient at compressor inlet
5.2.2 Stage Performance (Design Point Performance)

At the end of each stage, the following properties can be printed out for the design point performance:
(1) total temperature: \((R)\) or \((K)\)
(2) total pressure: \((\text{lbf/ft}^2)\) or \((\text{N/m}^2)\)
(3) static temperature: \((R)\) or \((K)\)
(4) static pressure: \((\text{lbf/ft}^2)\) or \((\text{N/m}^2)\)
(5) static density: \((\text{lbm/ft}^3)\) or \((\text{kg/m}^3)\)
(6) axial velocity: \((\text{ft/s})\) or \((\text{m/s})\)
(7) absolute velocity: \((\text{ft/s})\) or \((\text{m/s})\)
(8) relative velocity: \((\text{ft/s})\) or \((\text{m/s})\)
(9) tangential component of absolute velocity: \((\text{ft/s})\) or \((\text{m/s})\)
(10) tangential component of relative velocity: \((\text{ft/s})\) or \((\text{m/s})\)
(11) rotor wheel speed: \((\text{ft/s})\) or \((\text{m/s})\)
(12) absolute Mach number
(13) relative Mach number
(14) total temperature based on relative Mach number: \((R)\) or \((K)\)
(15) total pressure based on relative Mach number: \((\text{lbf/ft}^2)\) or \((\text{N/m}^2)\)
(16) absolute flow angle: (degree)
(17) relative flow angle: (degree)
(18) stream tube area: \((\text{ft}^2)\) or \((\text{m}^2)\)
(19) radius at which calculation is carried out: \((\text{ft})\) or \((\text{m})\)
(20) flow coefficient
(21) stage total pressure ratio
(22) stage adiabatic efficiency
(23) rotor total pressure ratio
(24) rotor adiabatic efficiency
(25) stage total temperature ratio

5.2.3 Overall Performance (Design Point Performance)

After all of stage performance is printed out, the following properties can be printed out.
(1) compressor inlet total temperature: \((R)\) or \((K)\)
(2) compressor inlet total pressure: (lbf/ft$^2$) or (N/m$^2$)
(3) corrected mass flow rate: (lbm/s) or (kg/s)
(4) overall total pressure ratio
(5) overall total temperature ratio
(6) overall adiabatic efficiency
(7) overall temperature rise: (F) or (C)
(8) relative flow angle at rotor inlet: BETISR(I) (degree)
(9) relative flow angle at rotor outlet: BET2SR(I) (degree)
(10) incidence for rotor: AINCSR(I) (degree)
(11) deviation for rotor: ADEVSRI (degree)
(12) absolute flow angle for stator inlet: BETISSI(I) (degree)
(13) absolute flow angle for stator outlet: BET2SS(I) (degree)
(14) incidence for stator: AINCSS(I) (degree)
(15) deviation for stator: ADEVSSSI (degree)
(16) stage inlet temperature: TD(I) (R) or (K)
(17) total pressure loss coefficient for stator: OMEGS(I)
(18) total pressure loss coefficient for rotor: OMEGR(I)

5.3 Output of Stage Performance

The performance of a stage is calculated for given initial and operating conditions with respect to the gaseous phase and the water droplets. At the exit of a blade row, the four major processes associated with two phase flow, namely (a) droplet impingement process; (b) centrifugal action on droplets; (c) heat and mass transfer processes between the two phases; and (d) droplet size adjustment; are taken into account. When the stage performance parameters are corrected for the afore-mentioned four processes, then one obtains the outlet conditions from a stage. The output of stage performance consist of two parts. First the following properties can be printed out before the afore-mentioned four processes are taken into account.

(1) stage total pressure ratio
(2) stage total temperature ratio
(3) stage adiabatic efficiency
(4) stage flow coefficient
(5) axial velocity: (ft/sec) or (m/sec)
(6) rotor speed: (ft/sec) or (m/sec)
(7) total pressure: (lbf/ft$^2$) or (N/m$^2$)
(8) static pressure: (lbf/ft$^2$) or (N/m$^2$)
(9) total temperature of gas phase: (R) or (K)
(10) static temperature of gas phase: (R) or (K)
(11) static density of gas phase: (lbm/ft$^3$) or (kg/m$^3$)
(12) static density of mixture: (lbm/ft$^3$) or (kg/m$^3$)
(13) axial velocity: (ft/s) or (m/s)
(14) absolute velocity: (ft/s) or (m/s)
(15) relative velocity: (ft/s) or (m/s)
(16) blade wheel speed: (ft/s) or (m/s)
(17) tangential component of absolute velocity: (ft/s) or (m/s)
(18) tangential component of relative velocity: (ft/s) or (m/s)
(19) acoustic speed: (ft/sec) or (m/s)
(20) absolute Mach number
(21) relative Mach number
(22) flow coefficient
(23) stream tube area (ft$^2$) or (m$^2$)
(24) absolute flow angle: (degree)
(25) relative flow angle: (degree)
(26) incidence: (degree)
(27) deviation: (degree)

After the stage parameters are corrected for the afore-mentioned four processes, the following second parts of output of stage performance can be printed out.

(1) stage total pressure ratio
(2) stage total temperature ratio
(3) stage adiabatic efficiency
(4) water vapor content: XV
(5) water content of small droplet: XW
(6) water content of large droplet: XWW
(7) total water content: XWT
(8) mass fraction of dry air: XAIR
(9) mass fraction of methane: XMETAN
(10) mass fraction of gaseous phase: XGAS
(11) mass flow rate of small droplet: WMASS (lbm/s) or (Kg/S)
(12) mass flow rate of large droplet: WRMASS (lbm/s) or (Kg/S)
(13) total mass flow rate of droplet: WTMASS (lbm/s) or (Kg/S)
(14) mass flow rate of dry air: AMASS (lbm/s) or (Kg/S)
(15) mass flow rate of methane: CHMASS (lbm/s) or (Kg/S)
(16) mass flow rate of water vapor: VMASS (lbm/s) or (Kg/S)
(17) mass flow rate of gaseous phase: GMASS (lbm/s) or (kg/S)
(18) mass flow rate of mixture: TMASS (lbm/s) or (Kg/S)
(19) specific humidity: WS
(20) density of air: RHOA (lbm/ft\(^3\)) or (Kg/m\(^3\))
(21) density of mixture: RHOM (lbm/ft\(^3\)) or (Kg/m\(^3\))
(22) density of gaseous phase: RHOG (lbm/ft\(^3\)) or (Kg/m\(^3\))
(23) temperature of gaseous phase: TG (R) or (K)
(24) temperature of small droplet: TW (R) or (K)
(25) temperature of large droplet: TWW (R) or (K)
(26) pressure: P (lbf/ft\(^2\)) or (N/m\(^2\))
(27) boiling point: TB (R) or (K)
(28) dew point: TDEW (R) or (K)

5.4 Output of Overall Performance

At the end of compressor, the overall performance can be printed out. The properties to be printed out are as follows:

(1) initial flow coefficient
(2) corrected speed of compressor and fraction of design corrected speed
(3) initial water content of small droplet
(4) initial water content of large droplet
(5) initial total water content
(6) initial relative humidity
(7) initial methane content
(8) compressor inlet total temperature: (R) or (K)
(9) compressor inlet total pressure: (lbf/ft\(^2\)) or (N/m\(^2\))
*(10) corrected mass flow rate of mixture: (lbm/s) or (Kg/S)
*(11) corrected mass flow rate of gaseous phase: (lbm/s) or (Kg/S)
(12) overall total pressure ratio
(13) overall total temperature ratio
(14) overall adiabatic efficiency
(15) overall temperature rise of gaseous phase: (F) or (c)

5.5 Diagnostic Printout

At the inlet of each stage, the flow coefficient is calculated. If
the flow coefficient gives the value of equivalent pressure ratio which
is less than 1.0 or the value of stage adiabatic efficiency which is
less than 0.0, the following message will appear. "FAI IS TOO BIG OR TOO
SMALL AT STAGE=." If this message appears, the computation for the
particular initial flow coefficient will be terminated and the next
initial flow coefficient will be read.

The iterative procedure is used to determine the Mach number. If the
desired accuracy can not be obtained after 50 times of iteration, the
following message will appear. "M DOES NOT CONVERGE AT STAGE=." If this
message appears, the final value of Mach number will be used and
computation will be continued.

When the axial velocity become either higher than local acoustic speed
or negative, the following message will appear: "VZ IS TOO HIGH OR TOO LOW." If this
message appears, the computation for the particular initial flow
coefficient will be terminated and the next initial flow coefficient will
be read.

* The mass flow rate corresponds to stream tube area specified in input
data. The mass flow rate which corresponds to compressor total flow
area is also printed out in the brackets.
CHAPTER VI

A TEST CASE

The application of the PURDU-WICSTK program is illustrated with a test case pertaining to the Test Compressor described in Appendix 1. The Test Compressor consists of the six axial stages of the ALLISON T63-A-5 engine compressor. The design point overall pressure ratio (mass averaged) is 2.9 with 3.0 lbm/sec of mass flow rate, and the design rotor speed is 51120 RPM.

The test case consists of the following predictions for the Test Compressor.

(i) Part I: Operation with air flow at a selected speed and throttle setting.
(ii) Part II: Operation with air-small droplet mixture flow at a selected speed and throttle setting; and
(iii) Part III: Operation with air-large droplet mixture flow at a selected speed and throttle setting.

The test case has been reproduced in Appendix 5.

6.1 Test Case Part I

The Test Case Part I demonstrates the use of the code for predicting the performance of a compressor which operates with air flow (only) at a selected speed and throttle setting. The performance prediction has been presented at the mean line of the Test Compressor.

6.1.1 Input Data

The input data for Test Case Part I are listed below as they are read in program MAIN.
Card 1:  \( NS = 6 \)

Card 2:  
\[
\begin{align*}
RRHUB(1) &= 0.770 \text{ inch} \\
RRHUB(2) &= 1.035 \text{ inch} \\
RRHUB(3) &= 1.232 \text{ inch} \\
RRHUB(4) &= 1.378 \text{ inch} \\
RRHUB(5) &= 1.489 \text{ inch} \\
RRHUB(6) &= 1.572 \text{ inch}
\end{align*}
\]

Card 3:  
\[
\begin{align*}
RC(1) &= 0.605 \text{ inch} \\
RC(2) &= 0.554 \text{ inch} \\
RC(3) &= 0.534 \text{ inch} \\
RC(4) &= 0.510 \text{ inch} \\
RC(5) &= 0.483 \text{ inch} \\
RC(6) &= 0.456 \text{ inch}
\end{align*}
\]

Card 4:  
\[
\begin{align*}
RBLADE(1) &= 16.00 \\
RBLADE(2) &= 20.00 \\
RBLADE(3) &= 20.00 \\
RBLADE(4) &= 25.00 \\
RBLADE(5) &= 28.00 \\
RBLADE(6) &= 32.00
\end{align*}
\]

Card 5:  
\[
\begin{align*}
STAGER(1) &= 34.25 \text{ degree} \\
STAGER(2) &= 29.96 \text{ degree} \\
STAGER(3) &= 27.37 \text{ degree} \\
STAGER(4) &= 28.30 \text{ degree} \\
STAGER(5) &= 29.17 \text{ degree} \\
STAGER(6) &= 29.75 \text{ degree}
\end{align*}
\]

Card 6:  
\[
\begin{align*}
SRHUB(1) &= 0.923 \text{ inch} \\
SRHUB(2) &= 1.145 \text{ inch} \\
SRHUB(3) &= 1.311 \text{ inch} \\
SRHUB(4) &= 1.445 \text{ inch} \\
SRHUB(5) &= 1.538 \text{ inch} \\
SRHUB(6) &= 1.580 \text{ inch} \\
SRHUB(7) &= 0.774 \text{ inch}
\end{align*}
\]

50
Card 7:  
SC(1) = 0.442 inch  
SC(2) = 0.412 inch  
SC(3) = 0.412 inch  
SC(4) = 0.412 inch  
SC(5) = 0.412 inch  
SC(6) = 0.412 inch  
SC(7) = 1.100 inch

Card 8:  
SBLADE(1) = 14.00  
SBLADE(2) = 26.00  
SBLADE(3) = 28.00  
SBLADE(4) = 32.00  
SBLADE(5) = 36.00  
SBLADE(6) = 30.00  
SBLADE(7) = 7.00

Card 9:  
SIGUMR(1) = 1.052  
SIGUMR(2) = 1.120  
SIGUMR(3) = 1.037  
SIGUMR(4) = 1.182  
SIGUMR(5) = 1.211  
SIGUMR(6) = 1.283

Card 10:  
SIGUMS(1) = 0.640  
SIGUMS(2) = 1.061  
SIGUMS(3) = 1.093  
SIGUMS(4) = 1.199  
SIGUMS(5) = 1.311  
SIGUMS(6) = 1.087  
SIGUMS(7) = 0.858

Card 11:  
FNF = 1.00
Card 12:  
XDIN  = 0.000  
ICENT  = 1  
XDDIN  = 0.000  
IICENT  = 1

Card 13:  
TOG  = 518.70 R  
TOW  = 513.70 R  
PO  = 2116.80 lb/ft²

Card 14:  
DIN  = 20.0 μm  
DDIN  = 600.0 μm

Card 15:  
FND  = 51120.0 RPM  
TOID  = 518.70 R  
PO1D  = 2116.80 lb/ft²

Card 16:  
XCH4  = 0.000  
RHUMID  = 0.00001 per cent

Card 17:  
FMWA  = 28.964  
FMWV  = 18.016  
FMWX  = 16.043

Card 18:  
PREB  = 50.00 per cent  
DLIMIT  = 100.0 μm

Card 19:  
STAGES(1) = 23.67 degree  
STAGES(2) = 25.62 degree  
STAGES(3) = 26.94 degree  
STAGES(4) = 28.41 degree  
STAGES(5) = 29.82 degree  
STAGES(6) = 38.99 degree  
STAGES(7) = 10.99 degree
Card 20: GAPR(1) = 0.125 inch
GAPR(2) = 0.125 inch
GAPR(3) = 0.125 inch
GAPR(4) = 0.125 inch
GAPR(5) = 0.125 inch
GAPR(6) = 0.125 inch

Card 21: GAPS(1) = 0.125 inch
GAPS(2) = 0.125 inch
GAPS(3) = 0.125 inch
GAPS(4) = 0.125 inch
GAPS(5) = 0.125 inch
GAPS(6) = 0.125 inch

Card 22: RRTIP(1) = 2.16 inch
RRTIP(2) = 2.16 inch
RRTIP(3) = 2.16 inch
RRTIP(4) = 2.16 inch
RRTIP(5) = 2.16 inch
RRTIP(6) = 2.16 inch

Card 23: SRTIP(1) = 2.16 inch
SRTIP(2) = 2.16 inch
SRTIP(3) = 2.16 inch
SRTIP(4) = 2.16 inch
SRTIP(5) = 2.16 inch
SRTIP(6) = 2.16 inch

Card 24: IPERFM = 2
IUNIT = 1

Card 25: IRAD = 2
Card 26:  
RT(1)  =  2.149 inch  
RT(2)  =  2.151 inch  
RT(3)  =  2.148 inch  
RT(4)  =  2.149 inch  
RT(5)  =  2.149 inch  
RT(6)  =  2.147 inch  

Card 27:  
RM(1)  =  1.426 inch  
RM(2)  =  1.575 inch  
RM(3)  =  1.642 inch  
RM(4)  =  1.722 inch  
RM(5)  =  1.789 inch  
RM(6)  =  1.836 inch  

Card 28:  
RH(1)  =  0.781 inch  
RH(2)  =  1.056 inch  
RH(3)  =  1.252 inch  
RH(4)  =  1.411 inch  
RH(5)  =  1.533 inch  
RH(6)  =  1.621 inch  

Card 29:  
ST(1)  =  0.934 inch  
ST(2)  =  1.152 inch  
ST(3)  =  1.318 inch  
ST(4)  =  1.453 inch  
ST(5)  =  1.548 inch  
ST(6)  =  1.592 inch  

Card 30:  
SM(1)  =  1.502 inch  
SM(2)  =  1.573 inch  
SM(3)  =  1.637 inch  
SM(4)  =  1.712 inch  
SM(5)  =  1.766 inch  
SM(6)  =  1.784 inch
Card 31:  
SH(1)  = 2.147 inch  
SH(2)  = 2.138 inch  
SH(3)  = 2.127 inch  
SH(4)  = 2.123 inch  
SH(5)  = 2.118 inch  
SH(6)  = 2.100 inch

Card 32:  
BLOCK(1) = 0.983  
BLOCK(2) = 0.976  
BLOCK(3) = 0.967  
BLOCK(4) = 0.949  
BLOCK(5) = 0.923  
BLOCK(6) = 0.902

Card 33:  
BLOCKS(1) = 0.978  
BLOCKS(2) = 0.966  
BLOCKS(3) = 0.945  
BLOCKS(4) = 0.928  
BLOCKS(5) = 0.908  
BLOCKS(6) = 0.863

Card 34:  
BET1MR(1) = 42.72 degree  
BET1MR(2) = 42.74 degree  
BET1MR(3) = 41.62 degree  
BET1MR(4) = 42.85 degree  
BET1MR(5) = 44.00 degree  
BET1MR(6) = 45.07 degree

Card 35:  
BET2MR(1) = 25.79 degree  
BET2MR(2) = 17.17 degree  
BET2MR(3) = 13.12 degree  
BET2MR(4) = 13.76 degree  
BET2MR(5) = 14.33 degree  
BET2MR(6) = 14.43 degree  

Card 36:  
- BET1MS(1) = 35.15 degree  
- BET1MS(2) = 40.11 degree  
- BET1MS(3) = 43.36 degree  
- BET1MS(4) = 45.00 degree  
- BET1MS(5) = 46.31 degree  
- BET1MS(6) = 48.71 degree  
- BET1MS(7) = 0.00 degree  

Card 37:  
- BET2MS(1) = 12.19 degree  
- BET2MS(2) = 11.13 degree  
- BET2MS(3) = 10.51 degree  
- BET2MS(4) = 11.81 degree  
- BET2MS(5) = 13.32 degree  
- BET2MS(6) = 29.28 degree  
- BET2MS(7) = 21.99 degree  

Card 38:  
- DMASS = 0.375538 lbn/sec  

Card 39:  
- PR12D(1) = 1.154  
- PR12D(2) = 1.165  
- PR12D(3) = 1.221  
- PR12D(4) = 1.237  
- PR12D(5) = 1.230  
- PR12D(6) = 1.215  

Card 40:  
- PR13D(1) = 1.152  
- PR13D(2) = 1.159  
- PR13D(3) = 1.213  
- PR13D(4) = 1.228  
- PR13D(5) = 1.221  
- PR13D(6) = 1.208
Card 41:  
ETARD(1) = 0.966  
ETARD(2) = 0.966  
ETARD(3) = 0.968  
ETARD(4) = 0.965  
ETARD(5) = 0.962  
ETARD(6) = 0.954

Card 42:  
SAREA(1) = 0.0103647 ft²  
SAREA(2) = 0.0092977 ft²  
SAREA(3) = 0.0080300 ft²  
SAREA(4) = 0.0069214 ft²  
SAREA(5) = 0.0059094 ft²  
SAREA(6) = 0.0051110 ft²

Card 43:  
SAREAS(1) = 0.0098704 ft²  
SAREAS(2) = 0.0084051 ft²  
SAREAS(3) = 0.0070775 ft²  
SAREAS(4) = 0.0060735 ft²  
SAREAS(5) = 0.0052626 ft²  
SAREAS(6) = 0.0046691 ft²  
SAREAS(7) = 0.0105669 ft²

Card 44:  
DELB1R(1) = 0.00  
DELB1R(2) = 0.00  
DELB1R(3) = 0.00  
DELB1R(4) = 0.00  
DELB1R(5) = 0.00  
DELB1R(6) = 0.00

Card 45:  
DELB1S(1) = 0.00  
DELB1S(2) = 0.00  
DELB1S(3) = 0.00  
DELB1S(4) = 0.00  
DELB1S(5) = 0.00  
DELB1S(6) = 0.00
Card 46:  
\[ X_{G1BLD}(1) = 0.000 \]
\[ X_{G1BLD}(2) = 0.000 \]
\[ X_{G1BLD}(3) = 0.000 \]
\[ X_{G1BLD}(4) = 0.000 \]
\[ X_{G1BLD}(5) = 0.000 \]
\[ X_{G1BLD}(6) = 0.000 \]

Card 47:  
\[ X_{G2BLD}(1) = 0.000 \]
\[ X_{G2BLD}(2) = 0.000 \]
\[ X_{G2BLD}(3) = 0.000 \]
\[ X_{G2BLD}(4) = 0.000 \]
\[ X_{G2BLD}(5) = 0.000 \]
\[ X_{G2BLD}(6) = 0.000 \]

Card 48:  
\[ X_{G3BLD}(1) = 0.000 \]
\[ X_{G3BLD}(2) = 0.000 \]
\[ X_{G3BLD}(3) = 0.000 \]
\[ X_{G3BLD}(4) = 0.000 \]
\[ X_{G3BLD}(5) = 0.000 \]
\[ X_{G3BLD}(6) = 0.000 \]

Card 49:  
\[ X_{WBLD}(1) = 0.000 \]
\[ X_{WBLD}(2) = 0.000 \]
\[ X_{WBLD}(3) = 0.000 \]
\[ X_{WBLD}(4) = 0.000 \]
\[ X_{WBLD}(5) = 0.000 \]
\[ X_{WBLD}(6) = 0.000 \]

Card 50:  
\[ X_{WWBLD}(1) = 0.000 \]
\[ X_{WWBLD}(2) = 0.000 \]
\[ X_{WWBLD}(3) = 0.000 \]
\[ X_{WWBLD}(4) = 0.000 \]
\[ X_{WWBLD}(5) = 0.000 \]
\[ X_{WWBLD}(6) = 0.000 \]
Card 51: BET2SS(1) = 21.89 degree  
BET2SS(2) = 19.09 degree  
BET2SS(3) = 19.33 degree  
BET2SS(4) = 20.18 degree  
BET2SS(5) = 21.15 degree  
BET2SS(6) = 34.86 degree  
BET2SS(7) = 15.61 degree

Card 52: FAI = 0.5000

Card 53: FAI = 9.99999

6.1.2 Output
The output for Test Case Part I is presented in Appendix 5. The details of the output obtained are described in Chapter V.

6.2 Test Case Part II
The Test Case Part II demonstrates the use of the code for predicting the performance of a compressor which operates with air-small droplet mixture flow at a selected speed and throttle setting. The water content of small droplet has been specified as four per cent by weight. The performance prediction has been presented at the mean line of the Test Compressor.

6.2.1 Input Data
The input data for Test Case Part II are the same as those for Test Case Part I except in regard to the following.

Card 12:  
XDIN = 0.040  
ICENT = 2  
XDDIN = 0.000  
IICENT = 1
6.2.2 Output
The output for Test Case Part II is presented in Appendix 5. The details of the output obtained are described in Chapter V.

6.3 Test Case Part III
The Test Case Part III demonstrates the use of the code for predicting the performance of a compressor which operates with air-large droplet mixture flow at a selected speed and throttle setting. The water content of large droplet has been specified as four per cent by weight. The performance prediction has been presented at the mean line of the Test Compressor.

6.3.1 Input Data
The input data for Test Case Part III are the same as those for Test Case Part I except in regard to the following.

Card 12: XDIN = 0.000
ICENT = 1
XDDIN = 0.040
IICENT = 2

6.3.2 Output
The output for Test Case Part III is presented in Appendix 5. The details of the output properties are described in Chapter V.
FIGURES
Fig. 1.1 Atmospheric Particle Size Ranges
Start

Read input data
Printout inputed data

Calculate the design point performance

Read initial flow coefficient ao

Calculate mass flow rate of gas phase and liquid phase from the inputed initial flow coefficient

Calculate stage performance

Calculate of droplet impingement on rotor blade

Calculation of droplet impingement on stator blade

Droplet size adjustment at rotor outlet

Droplet size adjustment at stator outlet

Calculation of heat transfer

Calculation of mass transfer

Printout stage performance

Subroutines

Figure 2.1 Flow Chart of Overall Program Structure
Figure 2.1 Flow Chart of Overall Program Structure (Continued)
Fig. 4.1 Geometry of Compressor Stage
Fig. 4.2 Angles Associated With a Typical Rotor Blade Element

- \( \beta_1, \beta_2 \) : Flow Angle
- \( \beta'_1, \beta'_2 \) : Blade Angle
- \( \gamma \) : Stager
- \( i \) : Incidence
- \( \delta \) : Deviation
Fig. 5.1 Station Number in Compressor Stages
APPENDIX 1

DETAIL OF TEST COMPRESSOR AND DRIVE ENGINE

1. Drive Engine

A T63-A-5 engine is used to drive the Test Compressor. The specifications, limits, and performance ratings for the Drive Engine are as follows:

- Design power output: 250 shp
- Ram power rating: 275 shp
- Design speeds:
  - Gas producer: 51,120 rpm (100%)
  - Power turbine: 35,000 rpm (100%)
  - Power output shaft: 6,000 rpm

The Drive Engine power turbine drives the Test Compressor through mechanical gearing. The power turbine speed has been increased to an output of 9,643 rpm at 100 per cent speed from the normal rating of 6,000 rpm. The Test Compressor is operated at 110 per cent (56,251.7 rpm) while the engine operates at 100 per cent or 51,120 rpm. One power turbine tachometer is used to monitor the Test Compressor speed. The ratio of the tachometer speed to the Test Compressor speed is 0.119676.

2. Test Compressor

The Test Compressor consists of the six axial stages of the ALLISON T63-A-5 engine compressor. The Test Compressor has been designed and built such that various stages of the compressor can be
assembled and tested. Thus the first two, the intermediate two or the last two stages can be tested if desired, as well as the unit with all of the six stages. Only the 6-stage unit has been used in the current tests.

The first stage of the Test Compressor is preceded by an inlet guide vane row which imparts swirl to the inlet air. The relative Mach number of the incoming air at the rotor inlet is thereby reduced as far as permissible without causing inlet blockage. The axial component features unshrouded rotors, cantilever stators, and double circular arc blading in all stages. The values of T-63 compressor design velocity diagram are presented in Table A.1.1. Table A.1.3 and A.1.4 present the hardware geometry and aerodynamic design data for rotor and stator, respectively.

Figure A.1.1. to Figure A.1.6 show the stage performance characteristics of Test Compressor supplied by the manufacturer. In each of the figures, the equivalent pressure ratio, \( \psi \), equivalent temperature ratio, \( \tau \), and stage adiabatic efficiency, \( \eta \), are presented in terms of flow coefficient, \( \phi \). The definitions of these parameters are as follows:

(i) flow coefficient: \( \phi \)

\[
\phi = \frac{V_z}{U_{\text{tip}}}
\]

(ii) equivalent pressure ratio: \( \psi \)

\[
\psi = \left\{ \left( \frac{U_{\text{tip}}}{T_{01} D} \right) \cdot \left( \frac{T_{01}}{U_{\text{tip}}^2} \right) \left( \frac{P_{\text{tip}}}{P_{01}} \right)^{\gamma / (\gamma - 1)} - 1 \right\} \frac{\gamma}{(\gamma - 1)}
\]

(iii) equivalent temperature ratio: \( \tau \)

\[
\tau = \left( \frac{U_{\text{tip}}}{T_{01} D} \right)^2 \cdot \left( \frac{\Delta T_{\text{tip}}}{U_{\text{tip}}^2} \right)
\]
### TABLE A.1.1

Test Compressor Design Velocity Diagram Values

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
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<tr>
<td>U</td>
<td>963.5</td>
<td>963.5</td>
<td>963.5</td>
<td>963.5</td>
<td>963.5</td>
<td>963.5</td>
</tr>
<tr>
<td>Vz1</td>
<td>508.4</td>
<td>544.1</td>
<td>547.0</td>
<td>554.9</td>
<td>554.1</td>
<td>543.7</td>
</tr>
<tr>
<td>Vθ1</td>
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<td>310.0</td>
<td>365.1</td>
<td>349.3</td>
<td>338.8</td>
<td>338.8</td>
</tr>
<tr>
<td>Wθ1</td>
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<td>598.4</td>
<td>614.2</td>
<td>624.7</td>
<td>629.9</td>
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<tr>
<td>a1</td>
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<td>31.6</td>
<td>31.5</td>
</tr>
<tr>
<td>β1</td>
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<td>47.6</td>
<td>47.9</td>
<td>48.5</td>
<td>49.3</td>
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<tr>
<td>M1abs</td>
<td>0.513</td>
<td>0.567</td>
<td>0.578</td>
<td>0.560</td>
<td>0.538</td>
<td>0.512</td>
</tr>
<tr>
<td>M1rel</td>
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<td>0.765</td>
<td>0.713</td>
<td>0.707</td>
<td>0.692</td>
<td>0.658</td>
</tr>
<tr>
<td>Vz2</td>
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<td>554.5</td>
<td>548.9</td>
<td>544.6</td>
</tr>
<tr>
<td>Vθ2</td>
<td>405.2</td>
<td>501.3</td>
<td>598.8</td>
<td>614.6</td>
<td>625.1</td>
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<tr>
<td>Wθ2</td>
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<td>462.2</td>
<td>364.7</td>
<td>348.9</td>
<td>338.4</td>
<td>333.2</td>
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<td>a2</td>
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<td>M2abs</td>
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<td>0.698</td>
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<td>0.660</td>
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<tr>
<td>M2rel</td>
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<td>0.643</td>
<td>0.574</td>
<td>0.552</td>
<td>0.528</td>
<td>0.506</td>
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</table>

Note: Symbols for Table A.1.1 are provided in Table A.1.2.
### TABLE A.1.2

Symbols for Test Compressor Design Velocity Diagram Values

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>Radius, inches</td>
</tr>
<tr>
<td>$U$</td>
<td>Rotor speed at $R$, ft/sec.</td>
</tr>
<tr>
<td>$V_z$</td>
<td>Air axial velocity, ft/sec.</td>
</tr>
<tr>
<td>$V_\theta$</td>
<td>Air absolute tangential velocity, ft/sec.</td>
</tr>
<tr>
<td>$W_\theta$</td>
<td>Air relative tangential velocity, ft/sec.</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Air absolute flow angle, degrees</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Air relative flow angle, degrees</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach number</td>
</tr>
</tbody>
</table>

**Subscript**

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rotor inlet</td>
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<tr>
<td>2</td>
<td>rotor outlet</td>
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<tr>
<td>abs</td>
<td>absolute</td>
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<tr>
<td>rel</td>
<td>relative</td>
</tr>
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### TABLE A.1.3
Test Compressor Design Data (Rotor)

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>R</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
</tr>
<tr>
<td>Camber Angle</td>
<td>$\theta$</td>
<td>22.6</td>
<td>15.9</td>
<td>18.0</td>
<td>19.7</td>
<td>20.9</td>
</tr>
<tr>
<td>Stagger</td>
<td>$\gamma$</td>
<td>46.1</td>
<td>42.3</td>
<td>36.5</td>
<td>36.1</td>
<td>36.0</td>
</tr>
<tr>
<td>Incidence</td>
<td>$i$</td>
<td>0.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Deviation</td>
<td>$\delta$</td>
<td>7.3</td>
<td>5.4</td>
<td>6.0</td>
<td>6.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Chord</td>
<td>$c$</td>
<td>0.605</td>
<td>0.554</td>
<td>0.534</td>
<td>0.510</td>
<td>0.483</td>
</tr>
<tr>
<td>Solidity</td>
<td>$\sigma$</td>
<td>0.713</td>
<td>0.815</td>
<td>0.787</td>
<td>0.941</td>
<td>0.997</td>
</tr>
<tr>
<td>Max. Thickness</td>
<td>$t$</td>
<td>0.036</td>
<td>0.039</td>
<td>0.037</td>
<td>0.036</td>
<td>0.034</td>
</tr>
<tr>
<td>Thickness-Chord Ratio</td>
<td>$t/c$</td>
<td>0.060</td>
<td>0.070</td>
<td>0.070</td>
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<tr>
<td>No. of Blades</td>
<td>$n$</td>
<td>16</td>
<td>20</td>
<td>20</td>
<td>25</td>
<td>28</td>
</tr>
</tbody>
</table>

Note: $R$, $c$, $t$ in [inches] and $\theta$, $\gamma$, $\delta$, $i$ in [degrees]

### TABLE A.1.4
Test Compressor Design Data (Stator)

<table>
<thead>
<tr>
<th>Stage</th>
<th>IGV</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>R</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
<td>2.161</td>
</tr>
<tr>
<td>Camber Angle</td>
<td>$\theta$</td>
<td>31.7</td>
<td>22.4</td>
<td>25.6</td>
<td>26.2</td>
<td>24.4</td>
<td>24.7</td>
</tr>
<tr>
<td>Stagger</td>
<td>$\gamma$</td>
<td>-15.9</td>
<td>31.3</td>
<td>36.3</td>
<td>36.6</td>
<td>36.8</td>
<td>37.4</td>
</tr>
<tr>
<td>Incidence</td>
<td>$i$</td>
<td>0.0</td>
<td>-2.0</td>
<td>-2.0</td>
<td>-2.0</td>
<td>-2.0</td>
<td>-2.0</td>
</tr>
<tr>
<td>Deviation</td>
<td>$\delta$</td>
<td>6.7</td>
<td>9.6</td>
<td>5.2</td>
<td>8.0</td>
<td>7.9</td>
<td>7.5</td>
</tr>
<tr>
<td>Chord</td>
<td>$c$</td>
<td>1.395</td>
<td>0.442</td>
<td>0.412</td>
<td>0.412</td>
<td>0.412</td>
<td>0.412</td>
</tr>
<tr>
<td>Solidity</td>
<td>$\sigma$</td>
<td>0.719</td>
<td>0.456</td>
<td>0.789</td>
<td>0.850</td>
<td>0.972</td>
<td>1.093</td>
</tr>
<tr>
<td>Max. Thickness</td>
<td>$t$</td>
<td>0.170</td>
<td>0.040</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Thickness-Chord Ratio</td>
<td>$t/c$</td>
<td>0.122</td>
<td>0.09</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>No. of Blades</td>
<td>$n$</td>
<td>7</td>
<td>14</td>
<td>26</td>
<td>28</td>
<td>32</td>
<td>36</td>
</tr>
</tbody>
</table>

Note: $R$, $c$, $t$ in [inches] and $\theta$, $\gamma$, $\delta$, $i$ in [degrees]
Fig. A.I.1 Performance Characteristics of Test Compressor (1st Stage)
Fig. A.1.2 Performance Characteristics of Test Compressor
(2nd Stage)
Fig. A.1.3 Performance Characteristics of Test Compressor
(3rd Stage)
Fig. A.1.4 Performance Characteristics of Test Compressor (4th Stage)
Fig. A.1.5 Performance Characteristics of Test Compressor (5th Stage)
Fig. A.1.6 Performance Characteristics of Test Compressor (6th Stage)
(iv) stage adiabatic efficiency: $\eta$

$$\eta = T_{01} \left( \frac{P_{02}}{P_{01}} \right)^{\frac{Y-1}{Y}} - 1 \right) \frac{1}{\Delta T_0} = \frac{(\psi \frac{Y-1}{Y} - 1)}{\tau}$$

where $\Delta T_0$ is stage total temperature rise, $P_0$ total pressure, $T_0$ total temperature, $V_z$ axial velocity, $U_{tip}$ blade tip wheel speed, $\gamma$ specific heat ratio. The subscripts 1 and 2 mean inlet and outlet, respectively, and D design value.

Figure A.1.7 shows overall performance characteristics of Test Compressor supplied by the manufacturer. The performance parameters are the following:

(1) Corrected mass flow rate $= \frac{\dot{m}\sqrt{\theta}}{\delta}$

where $\dot{m}$ = mass flow rate
$T_{01}$ = compressor inlet pressure
$P_{01}$ = compressor inlet temperature
$\theta$ = $T_{01}/T_{ref}$
$\delta$ = $P_{01}/P_{ref}$
$T_{ref}$ = 58.7°F(15.2°C)
$P_{ref}$ = 14.7 psi (1.0132 x $10^5$N/m$^2$)

(2) Corrected speed $= \frac{N}{\sqrt{\theta}}$

where $N$ = rotor speed (RPM)

(3) Overall total pressure ratio $= \frac{P_{02}}{P_{01}}$

where $P_{01}$ = compressor inlet total pressure
$P_{02}$ = compressor outlet total pressure

(4) Overall adiabatic efficiency $= \eta = \frac{T_{01}}{\Delta T_0} \left( \frac{P_{02}}{P_{01}} \right)^{\frac{Y-1}{Y}} - 1 \right)$

where $T_{01}$ = compressor inlet total temperature
$\Delta T_0$ = compressor total temperature rise

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Fig. A1.7 Overall Performance of Test Compressor
EFFECT OF WATER ON AXIAL FLOW COMPRESSORS. PART I. ANALYSIS AND--ETC(U)

JUN 81 T Tsuchiya, S N Murthy

F33615-78-C-2401

UNCLASSIFIED

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NL
\[ \frac{P_{02}}{P_{01}} = \text{overall total pressure ratio} \]
\[ \gamma = \text{ratio of specific heats} \]

3. **Limitations**

The Test Compressor is driven, through a mechanical gear train, by the power turbine of the Drive Engine. The 6-stage Test Compressor has been utilized in the past for up to 30 hours. The available lifetime for further use of that Test Compressor has been uncertain.

The Test Compressor has a plastic coating on the casing that supports the stator blade rings. The mechanical and thermal strength of the coating has been uncertain since the casing was built over ten years ago and may have aged. At design point, the Test Compressor temperature rise is about 192°F, (106°C) when the inlet-air temperature is 58.7°F, (15.2°C). A casing has been replaced by a second casing during preliminary testing.

The throttle regulating the Test Compressor mass flow at any given speed of operation consists of a conical center piece that can be set at any desired location concentrically in a diverging section which is then opened to atmospheric conditions following a straight duct. The center piece can be moved utilizing an electric motor. The throttle (annulus) area that is available during center piece motion is shown in Fig. A.1.8. It is possible to set the throttle to within a tenth of an inch (about 2.0 mms) during horizontal traverse of the throttle centerpiece. At a given Test Compressor speed, a chosen throttle setting may yield one of two types of performance: (i) when it is unchoked, the pressure ratio across the throttle (the downstream pressure being related to the atmospheric pressure) determines the mass flow throughout the Test Compressor; and (ii) when the throttle area is too large for passing the mass flow through the Test Compressor with a particular set of inlet conditions, the Compressor will operate under free-wheeling conditions.

The Test Compressor assembly with the gear box connecting it to the Drive Engine is such that there is no simple access to its outlet section for locating adequate instrumentation or adjusting probes to establish compressor outlet conditions. The gear box disassembly and removal of the compressor outlet ducting are required each time any access is desired to the compressor outlet section.
Fig. A.1.8 Flow Area vs. Throttle Setting
3.1 Refurbishment

The Drive Engine and the Test Compressor have been refurbished in the following respects by the Detroit Diesel Allison of Indianapolis, who are the original manufacturers of both the units.

(1) Engine fuel flow control;
(2) Drive shaft interconnecting the Drive Engine and the Test Compressor;
(3) Test Compressor gear box;
(4) Test Compressor bearings; and
(5) The 6-stage assembly of Test Compressor, including balancing.

Following this refurbishment and additional work undertaken at Purdue University, proof-runs undertaken on the Drive Engine - Test Compressors installation showed feasibility of satisfactory operation of the test unit.
APPENDIX 2

STAGE PERFORMANCE CALCULATION

There are two options in the PURDU-WICSTK Code for the calculation of stage performance:

1. based on given stage characteristics, and
2. through the estimation of work done and losses in a stage, based on an analytical model.

In both cases, several approximations are required. It may also be recalled that the stage performance calculation being discussed here pertains only to establishing the stage work done, and the consequent temperature and pressure rise, and the stage losses as they occur between the leading and trailing edges of a blade. As stated in Chapter II, and also in Reference 22, the final exit conditions from a stage are established after correcting the stage outlet conditions for various two phase flow effects.

In calculating the stage performance, it is necessary to take into account the presence of droplets in the fluid, and their motion, particularly their impact on the blades. Such impaction leads to the formation of a film on the blade surface, composed of water from unreboun droplets, and a change in the boundary layer and separation characteristics. Thus, the stage characteristics become different for a droplet-laden gas flow from those for a single phase gas. The change in stage characteristics arises through modification of (a) momentum thickness of boundary layer, (b) diffusion factor and (c) deviation angle.

It may be stated at the outset that no correlations of compressor, cascade or even single airfoil performance data are available for two phase flow. It is therefore necessary to model compressor flow based on a number of approximations, in turn related to physical process models.
In order to account for various drop sizes that may arise in a spray, it has been suggested, in Reference 22 and again in Chapter 11, that two classes of droplets be identified, one referred to as "small" and the other as "large." In adjusting droplet sizes for any reason, it is assumed that small droplets may only remain small, while large droplets may become small enough to belong to the small droplet class. From the point of view of blade passage flow, the principal distinction between small and large droplets is, as has been mentioned earlier, that small droplets are sufficiently small and follow the gas phase streamlines; but large droplets, which are in order of about 100 μm in diameter, are assumed to have equal probability of motion in all directions in the forward sector. In addition, it is assumed that only small droplets may absorb part of the work input. Other distinctions between the two classes of droplets arise from the foregoing and are taken into account in developing compressor flow models for the two classes of droplets.

In order to simplify calculations of stage losses, three procedures have been developed as follows:

(1) procedure when the compressor operate with a single (gas) phase;
(2) procedure when only small droplets are present; and
(3) procedure when large droplets are present either by themselves or along with small droplets.

Typical velocity diagram for an axial compressor stage is presented in Fig.A.2.1.

A.2.1. Procedure of Gas Phase Operation

One can use either (1) available stage characteristics or (2) an analytical/correlation method for obtaining stage characteristics. For the Test Compressor employed in this investigation, the analytical/correlation method recommended is based on References 23 and 24.

A.2.1.1. Use of Available Stage Characteristics

The stage performance calculation for gas phase operation, with use of available stage characteristics, are carried out as follows:
Fig. A.2.1 Typical Velocity Diagram for a Compressor Stage
(1) From given inlet conditions or the previous stage outlet conditions, the total temperature, $T_{01}$, and the total pressure, $P_{01}$, are known.

(2) Calculate the density based on $T_{01}$ and $P_{01}$

$$\rho_{01} = \frac{P_{01}}{R_m T_{01}}$$

(3) Assume Mach number $M_a$.

(4) Calculate static temperature, $T$, and density, $\rho$.

$$\rho = \left[1 + (\gamma - 1)M_a^2/2\right]^{-1}/(\gamma - 1) \cdot \rho_{01}$$

$$T = \left[1 + (\gamma - 1)M_a^2/2\right]^{-1} \cdot T_{01}$$

(5) Calculate acoustic speed

$$a = \left(\gamma R_m T g_c\right)^{1/2}$$

(6) Calculate the axial velocity

$$V_z = \dot{m}/pA$$

(7) Calculate the absolute velocity at rotor inlet, $V_1$.

$$V_1 = V_z/cos \alpha_1$$

(8) Calculate Mach number

$$M = V_1/a = M_C$$

(9) Compare the assumed Mach number, $M_a$, with the calculated one, $M_C$. If $M_C$ agrees within prescribed limits with $M_a$, proceed to the next step. Otherwise, steps 3 to 9 should be repeated until a satisfactory accuracy is obtained.

(10) Calculate the flow coefficient, $\phi$, at the entrance to the stage under consideration.

$$\phi = V_z/U_{tip}$$
Enter the stage characteristics curve at the value of $\phi$ and obtain the equivalent pressure ratio, $\psi$, equivalent temperature ratio, $\tau$, and stage adiabatic efficiency, $\eta$.

The definitions of $\psi$, $\tau$, and $\eta$ are as follows:

(i) flow coefficient: $\phi$

$$\phi = \frac{V_z}{U_{tip}}$$

(ii) equivalent pressure ratio:

$$\psi = \left[ \frac{U_{tip}^2}{T_{O1}} \right]_D \left( \frac{T_{O1}}{U_{tip}^2} \right) \left( \frac{P_{O2}}{P_{O1}} \right) \left( \frac{(Y-1)/\gamma}{-1} + 1 \right)^{\gamma/(Y-1)}$$

(iii) equivalent temperature ratio: $\tau$

$$\tau = \left( \frac{U_{tip}^2}{T_{O1}} \right)_D \left( \frac{\Delta T_o}{U_{tip}^2} \right)$$

(iv) stage adiabatic efficiency:

$$\eta = T_{O1} \left( \frac{P_{O2}}{P_{O1}} \right)^{\gamma-1} \left( \frac{1}{\Delta T_0} \right) = \frac{(\psi(Y-1)/\gamma-1)}{\tau}$$

where $\Delta T_o$ is stage total temperature rise, $P_0$ total pressure, $T_0$ total temperature, $V_z$ axial velocity, $U_{tip}$ blade tip wheel speed, $\gamma$ specific heat ratio. The subscripts 1 and 2 mean inlet and outlet, respectively, and D design value.

The equivalent pressure ratio, $\psi$, equivalent temperature ratio, $\tau$, and stage adiabatic efficiency, $\eta$, may be expressed in terms of flow coefficient as follows:

$$\psi = A_1 + B_1 \phi + C_1 \phi^2 + D_1 \phi^3 + E_1 \phi^4 + F_1 \phi^5 + G_1 \phi^6$$

$$\eta = A_2 + B_2 \phi + C_2 \phi^2 + D_2 \phi^3 + E_2 \phi^4 + F_2 \phi^5 + G_2 \phi^6$$

$$\tau = A_3 \phi + B_3$$
(12) Once the values of $\psi$, $\tau$, and $\eta$ corresponding to $\phi$ are obtained, the stage outlet properties can be calculated from their definitions. Actually two of them are enough to determine the stage outlet properties. In the present calculation scheme, the equivalent temperature rise ratio, $\tau$, and the stage adiabatic efficiency, $\eta$, are used. The stage total temperature rise, $\Delta T_0$, stage and total temperature ratio, $T_{02}/T_{01}$, and stage total pressure ratio, $P_{02}/P_{01}$, are given by the following:

$$\Delta T_0 = \tau \frac{U_{tip}}{U_{tip}/T_{01}}$$

$$T_{02}/T_{01} = 1 + \frac{\Delta T_0}{T_{01}}$$

$$P_{02}/P_{01} = \left(1 + \frac{\Delta T_0}{T_{01}}\right)^{\gamma/(\gamma-1)}$$

A.2.1.2. Use of Analytical/Correlation Method

The stage performance calculation for gas phase operation is carried out using the analytical/correlation method as follows:

1. From given inlet conditions or the previous stage exit conditions, the total temperature, $T_{01}$, and total pressure, $P_{01}$, are obtained.
2. Calculate specific heat ratio corresponding to the temperature.
3. Calculate the stagnation density
4. Assume a value for Mach number, $M_a$.
5. Calculate the static density and temperature.
(6) Calculate the acoustic speed

\[ a_1 = (\gamma RT_1 g_c)^{0.5} \]

(7) Calculate the axial velocity

\[ V_{z1} = \dot{m}/\rho_1 A_1 \]

(8) Calculate the absolute velocity

\[ V_1 = V_{z1}/\cos a_1 \]

(9) Calculate the Mach number, \( M_c \).

\[ M_c = V_{z1}/a_1 \]

(10) Compare the assumed value of Mach number, \( M_a \), with the calculated one, \( M_c \). If \( M_a \) agrees within prescribed limits with \( M_c \), proceed to the next step. Otherwise, steps (4) to (9) must be repeated.

(11) Calculate the components of velocity from the velocity diagram at rotor inlet as follows:

\[ V_1 = V_{z1}/\cos a_1 \]

\[ V_{\theta1} = V_{z1} \tan a_1 \]

\[ W_{\theta1} = U_1 - V \]

\[ W_1 = (V_{z1}^2 + W_{\theta1}^2)^{0.5} \]

\[ \beta_1 = \tan^{-1}(W_{\theta1}/V_{z1}) \]

(12) Calculate relative Mach number at rotor inlet

\[ M_{r1} = W_1/a_1 \]

(13) Calculate static pressure at rotor inlet

\[ p_1 = (T_{01}/T_1)^{-\gamma/\gamma-1} \cdot P_{01} \]
(14) Calculate total pressure at rotor inlet based on the relative Mach number, $M_r$.

$$P_{01,r} = \left\{ 1 + (\gamma - 1)M_r^2 / 2 \right\} \frac{\gamma}{\gamma - 1} \cdot P_1$$

(15) Assuming $V_{22}$, calculate the total pressure loss coefficient across rotor and rotor outlet flow angle.

(16) Calculate the components of velocity at rotor outlet as follows:

$$W_{\theta 2} = V_{22} \tan \beta_2$$
$$V_{\theta 2} = U_2 - W_{\theta 2}$$
$$W_2 = (V_{22}^2 + W_{\theta 2}^2)^{0.5}$$
$$V_2 = (V_{22}^2 + V_{\theta 2}^2)^{0.5}$$
$$\alpha_2 = \tan^{-1} (V_{\theta 2} / V_{22})$$

(17) Calculate the total temperature at rotor outlet.

$$T_{02} = T_{01} + (U_2 V_{\theta 2} - U_1 V_{\theta 1}) / c_p g_c J$$

(18) Calculate static temperature at rotor outlet.

$$T_2 = T_{02} - V_2^2 / 2 c_p g_c J$$

(19) Calculate acoustic speed at rotor outlet.

$$a_2 = (\gamma R T_2 g_c)^{0.5}$$

(20) Calculate absolute and relative Mach number at rotor outlet.

$$M_2 = V_2 / a_2$$
$$M_{r_2} = W_2 / a_2$$
(21) Calculate total pressure loss factor across rotor.

\[
\frac{P_{\text{loss},r}}{P_{0,1,\text{r}}} = \frac{P_{\text{loss},r}}{P_{0,1,\text{r}}} = \left(1 - \frac{P}{P_{0,1,\text{r}}}ight)
\]

where

\[
\frac{P_{\text{loss},r}}{P_{0,1,\text{r}}} = \left(\frac{T_{\text{loss},r}}{T_{0,1,\text{r}}}ight)^{\frac{\gamma - 1}{\gamma}}
\]

\[
= \left[1 + \frac{\gamma - 1}{2} \frac{U^2}{RT_{0,1,\text{r}}} \left(1 - \left(\frac{P_{\text{loss},r}}{P_{0,1,\text{r}}}\right)^2\right)^{\frac{\gamma - 1}{2}}\right]
\]

(22) Calculate total pressure ratio across rotor, and total and static pressure at rotor outlet.

\[
\frac{P_{\text{r}}}{P_{0,1}} = \left(\frac{T_{\text{r}}}{T_{0,1}}\right)^{\frac{\gamma - 1}{\gamma}} \cdot \frac{P_{\text{r}}}{P_{0,1,\text{r}}} \cdot \frac{P_{\text{r}}}{P_{0,1,\text{r}}}^{-1}
\]

\[
P_{\text{r}} = \left(\frac{P_{\text{r}}}{P_{0,1}}\right) P_{0,1}
\]

\[
P_2 = \left(1 + \frac{\gamma - 1}{2} M_2^2\right)^{\frac{-\gamma}{\gamma - 1}} \cdot P_0
\]

(23) Calculate density at rotor outlet.

\[
P_2 = P_2/RT_2
\]

(24) Calculate the axial velocity at rotor outlet.

\[
V_{Z2} = \frac{\dot{m}}{\rho_2 A_2}
\]

(25) Compare the calculated value of \(V_{Z2}\) in (24) with the assumed \(V_{Z2}\) in (15). Iterate steps (15) to (24) until a desired accuracy is obtained.
(26) Calculate total pressure at rotor outlet.

\[ P_{02} = \left\{ 1 + (\gamma - 1)M_2^2 / 2 \right\} \frac{\gamma}{(\gamma - 1)} \cdot P_2 \]

(27) Calculate the total pressure loss coefficient across stator, \( \bar{\omega}_S \), and stator outlet angle \( \alpha_s \).

(28) Calculate total pressure loss factor across stator.

\[ \frac{P_{03}}{P_{02}} = 1 - \bar{\omega}_S \left( 1 - \frac{P_2}{P_{02}} \right) \]

(29) Calculate the total pressure ratio and total temperature ratio across the stage.

\[ PR = \frac{P_{03}}{P_{01}} = \left( \frac{T_{03}}{T_{01}} \right)^{\frac{\gamma - 1}{\gamma}} \cdot \left( \frac{P_{02, r}}{P_{01, r}} \right) \cdot \left( \frac{P_{02, r i}^{-1}}{P_{02, r i}} \right) \cdot \left( \frac{P_{01}}{P_{02}} \right) \]

\[ TR = \frac{T_{03}}{T_{01}} \]

(30) Obtain total pressure and temperature at stator outlet.

\[ P_{03} = \left( \frac{P_{03}}{P_{02}} \right) \cdot P_{02} \]

\[ T_{03} = T_{02} \]

(31) Calculate the average value of specific heat ratio.

(32) Calculate the stage efficiency.

\[ \eta = \frac{PR^{(\gamma - 1)/\gamma} - 1}{TR - 1} \]
A.2.2 Procedure when Small Droplets are Present.

When all of the droplets present at entry to a stage can be categorized as small droplets, the following assumptions are introduced.

(1) Droplets follow gas phase streamlines.

(2) A fraction of the droplets impacting the blades undergo rebound. The balance of impacting droplets move over the blade surface in the form of a thin film. The momentum of the thin film is negligible.

(3) The development of the boundary layer over the blade surface can be based on Reference 25. The following assumptions are made in that Reference: (i) droplets do not interact with one another; (ii) a two phase boundary layer exists; and (iii) the momentum thickness for the two phases can be superposed after they are obtained in two parts.

(4) The deviation angle remains the same in two phase flow as in single phase flow. The reasoning is that diffusion and transport of particles can be neglected as being small and, in any case, as balancing each other.

(5) The loss coefficient for two phase flow is thus the sum of the loss coefficient for each phase. The loss coefficient for the liquid phase may also be added in an appropriate form to the stage efficiency for a stage obtained during operation with air in order to obtain the stage efficiency for two phase flow.

(6) Considering a blade passage flow, between two neighboring blades, away from solid boundaries, the drag due to droplets can be calculated assuming Stokes drag relation. The number of droplets suffering such drag is the sum of the number of non-impacting droplets and the number of rebound droplets.
(7) The overall loss is obtained by adding the losses described under (5) and (6).

A.2.2.1 Use of Available Stage Characteristics

In dealing with a mixture containing small droplets, it is assumed that (a) gas phase and the small droplets behave in the same fashion in absorbing work input as a gas, and (b) the influence of small droplets arises in the determination of (a) the flow coefficient and (b) the stage losses.

In using gas flow stage characteristics for a mixture with small droplets, the pressure rise for the gas phase, the temperature rise of water and efficiency are determined for the relevant value of flow coefficient from the gas phase characteristics, and then, the efficiency is further modified to account for the presence of small droplets.

The stage performance calculation for a mixture with small droplets can thus be carried out using the available stage characteristics as follows:

(1) From the previous stage outlet properties, the gas phase total temperature, $T_{01,g}$, and the total pressure, $P_{01}$, are known.

(2) Calculate the gas constant, specific heat at constant pressure, and specific heat ratio of the gas phase.

(3) Calculate the stagnation density of gas phase.

(4) Assume a value for Mach number, $M_a$.

(5) Calculate the static density and static temperature of the gas phase.

(6) Calculate the acoustic speed in the gas phase.

(7) Calculate the acoustic speed in the mixture, $a$. 

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(8) Calculate the density of the mixture.

\[ \rho_m = \left( \frac{x_g \rho_g + x_w \rho_w}{\rho_g + \rho_w} \right)^{-1} \]

(9) Calculate the axial velocity.

\[ V_z = \frac{\dot{m}_m}{\rho_m A} \]

(10) Calculate the absolute velocity.

\[ V_1 = \frac{V_z}{\cos \alpha_1} \]

where \( \alpha_1 \) = air outlet angle of the previous stage stator.

(11) Calculate the Mach number, \( M_c \).

\[ M_c = \frac{V_1}{a} \]

(12) Compare the assumed Mach number, \( M_a \), with the calculated one, \( M_c \). If \( M_a \) agrees reasonably well with \( M_c \), proceed to the next step. Otherwise, steps (4) to (11) must be repeated.

(13) Calculate the flow coefficient at the entrance of the stage

\[ \phi = \frac{V_z}{U_{tip}} \]

(14) Enter the stage characteristic curve at the foregoing value of \( \phi \).

The compressor stage characteristics, described in A.2.1.1., which apply to air flow through the compressor, have been utilized in this calculation for obtaining the stage temperature ratio and stage adiabatic efficiency for the mixture of air and small droplets. It may be recalled that the stage temperature rise corresponding to a mixture flow coefficient has to be apportioned between the gas and the liquid phases. The gas phase then undergoes a change in temperature and pressure while the liquid phase undergoes only a temperature change.
Utilizing the stage temperature ratio and adiabatic efficiency, one can then calculate the stage pressure ratio and the change in water temperature. In the current method of calculating stage performance for two phase flow, all of the other effects due to the presence of droplets are taken into account at the exit of the stage under consideration.

(15) Apportion energy input into the mixture.

Regarding apportionment of energy input into the mixture in a stage, one proceeds as follows. The work input is expressed by the following relations:

$$
\Delta H_0 = (\Delta H_0)_1 + (\Delta H_0)_2 + (\Delta H_0)_3 + (\Delta H_0)_4
$$

where

- $\Delta H_0$ : actual work input in rotor;
- $(\Delta H_0)_1$ : work input to gas phase;
- $(\Delta H_0)_2$ : work input absorbed by droplets which do not impinge upon blade surface;
- $(\Delta H_0)_3$ : work input absorbed by water droplets which impinge upon blade surface, adhere to form a film and are re-entrained from the trailing edge; and
- $(\Delta H_0)_4$ : work input absorbed by droplets which impinge upon blade surface and rebound.

Defining mass fractions as follows:

- $x_g$ : mass fraction of gas phase.
- $x_{w1}$ : mass fraction of water which does not impinge upon blade surface
- $x_{w2}$ : mass fraction water which impinges on the blade surface and rebounds
- $x_{w3}$ : mass fraction of water which is re-entrained from the trailing edge.
and noting that

\[ x_g + x_{w1} + x_{w2} + x_{w3} = 1, \]

one can express the work input fractions as follows in terms of the stage work done factor, \( \lambda \).

\[
(\Delta H_0)_1 = \lambda U_2 (W_{\theta 1} - W_{\theta 2}) x_g \\
(\Delta H_0)_2 = \lambda U_2 (W'_{\theta 1} - W'_{\theta 2}) x_{w1}
\]

where \( W_{\theta 1} \) and \( W'_{\theta 1} \) are relative inlet whirl velocities of the gas phase and water droplets which do not impinge upon the blade surface, respectively, and \( W'_{\theta 2} \) and \( W_{\theta 2} \) are the same velocities at outlet.

Also, from physical considerations, the angular momentum change of water which impinges on the surface and adheres to form films and is finally re-entrained from the trailing edge can be considered to be negligible. Therefore,

\[(\Delta H_0)_3 = 0\]

Then, \((\Delta H_0)_4\) can be calculated by writing

\[(\Delta H_0)_4 = \Delta H_0 - (\Delta H_0)_1 - (\Delta H_0)_2\]

The total work input, \( \Delta H_0 \), is calculated from the stage performance curves. In the present analysis, since we are considering small droplets, the velocity lag between gas phase and water droplet can be considered to be negligible. Accordingly \( W'_{\theta 1} \) and \( W'_{\theta 2} \) can be set to be the same as \( W_{\theta 1} \) and \( W_{\theta 2} \).

From \((\Delta H_0)_1\), \((\Delta H_0)_2\), \((\Delta H_0)_3\), and \((\Delta H_0)_4\), the total temperature rise can be calculated for each phase.

(16) Obtain the total pressure loss because of the increase in momentum thickness of the boundary layer due to the existence of small droplets in the boundary layer.
(17) Obtain the total pressure loss due to the Stokesian drag of water droplets outside boundary layer.

(18) Calculate the stage outlet total pressure as follows:

\[ P_{02} = P_{01} - \Delta P_\theta - \Delta P_S \]

where \( P_{02} \) is the stage outlet total pressure obtained from the available stage characteristics, \( \Delta P_\theta \) is the total pressure loss due to the increase in momentum thickness because of the existence of small droplets in the boundary layer, and \( \Delta P_S \) is the total pressure loss due to the Stokesian drag of water droplets in the free stream outside the boundary layer.

It may be pointed out that in view of the assumption pertaining to motion of small droplets (with zero relative velocity with respect to gas phase), the correction to stage pressure rise due to Stokesian drag becomes zero for small droplets.

(19) Calculate the stage total pressure ratio.

A.2.2.2 Use of Analytical/Correlation Method

In using the analytical/correlation method for the flow of a mixture with small droplets, the basic procedure is the same as when utilizing available stage characteristics, Appendix Section A.2.2. The pressure rise for the gas phase and the temperature rise of water are determined from the mixture turning angle over a blade. The losses are established based on (a) the relation (due to Lieblein) between the loss coefficient and the pressure loss; the loss coefficient in turn related to the momentum thicknesses of the blade boundary layer due to the gas phase and the droplets; and (b) the Stokesian drag of droplets in the free stream. The latter, of course, is zero for small droplets, by definition.

The stage performance calculation for a mixture with small droplets is carried out using the analytical/correlation method as follows:

(1) From the given inlet condition or the previous stage properties, the gas phase total temperature, \( T_{01,g} \), and total pressure, \( P_{01} \), are obtained.
(2) Calculate the gas constant, \( R_g \), specific heat constant pressure, \( c_{pg} \) and specific heat ratio of gas phase, \( \gamma \).

(3) Calculate the stagnation density of gas phase.

\[
P_{01,g} = \frac{P_{01}}{R T_{01,g}}
\]

(4) Assume a value for Mach number, \( M_a \).

(5) Calculate the static density and temperature of gas phase.

\[
\rho_{g1} = \left[1 + (\gamma - 1)\frac{M_a^2}{2}\right]^{-1/(\gamma - 1)} \rho_{01,g}
\]

\[
T_{g1} = \left[1 + (\gamma - 1)\frac{M_a^2}{2}\right] T_{01,g}
\]

(6) Calculate the acoustic speed in the gas phase \( a_{g1} \).

\[
a_{g1} = (\gamma R g_{g1} c_g)^{0.5}
\]

(7) Calculate the acoustic speed in the mixture, \( a_i \).

(8) Calculate the density of the mixture

\[
\rho_m = \left\{\frac{x_g}{\rho_g} + \frac{x_w}{\rho_w}\right\}^{-1}
\]

(9) Calculate the axial velocity

\[
V_{z1} = \frac{\dot{m}_m}{\rho_1 A_1}
\]
(10) Calculate the absolute velocity

\[ V_1 = V_{z1}/\cos \alpha_1 \]

(11) Calculate the Mach number, \( M_c \).

\[ M_c = V_1/a_1 \]

(12) Compare the assumed Mach number, \( M_a \), with the calculated one, \( M_c \). If \( M_a \) agrees within prescribed limits with \( M_c \), proceed to the next step. Otherwise, steps (4) to (11) must be repeated.

(13) Calculate the components of velocity at rotor inlet as follows:

\[ V_1 = V_{z1}/\cos \alpha_1 \]
\[ V_{\theta 1} = V_{z1}/\tan \alpha_1 \]
\[ W_{\theta 1} = U_1 - V_{\theta 1} \]
\[ W_1 = (V_{z1}^2 + W_{\theta 1}^2)^{1/2} \]
\[ \beta_1 = \tan^{-1}(W_{\theta 1}/V_{z1}) \]

(14) Calculate relative Mach number at rotor inlet

\[ M_{r1} = W_1/a_1 \]

(15) Calculate static pressure at rotor inlet

\[ p_1 = (T_{01}g/T_{g1})^{\gamma/(\gamma -1)} \cdot p_{01} \]
(16) Calculate total pressure at rotor inlet based on the relative Mach number, $M_{r1}$.

\[ P_{01,r} = (1 + (\gamma - 1) M_{r1}^2 / 2)^{\gamma / (\gamma - 1)} P_1 \]

(17) Assuming $V_{z2}$ the total pressure loss coefficient across rotor due to gas phase, $\bar{\omega}_{g,R}$, and rotor outlet angle $\beta_2$.

(18) Obtain the total pressure loss coefficient due to the increase of momentum thickness because of the existence of small droplets in the boundary layer over a rotor blade surface $\bar{\omega}_{\theta,R}$.

(19) Obtain the total pressure loss across rotor due to the Stokesian drag of water droplets outside boundary layer $\bar{\omega}_{s,R}$.

(20) Calculate the components of velocity at rotor outlet as follows:

\[ W_{\theta 2} = V_{z2} \tan \beta_2 \]
\[ V_{\theta 2} = U_2 - W_{\theta 2} \]
\[ W_2 = (V_{z2}^2 + W_{\theta 2}^2)^{0.5} \]
\[ V_2 = (V_{z2}^2 + V_{\theta 2}^2)^{0.5} \]
\[ \alpha_2 = \tan^{-1}(V_{\theta 2}/V_{z2}) \]

(21) Calculate the work input.

\[ \Delta H_0 = (U_2 V_{\theta 2} - U_1 V_{\theta 1}) / g_c J \]

(22) Apportion work input to the mixture constituents as described in item (14) of A.2.2.1.
(23) Calculate static temperature of gas phase at rotor outlet.

\[ T_{g_2} = T_{o_2,g} - \frac{V^2}{2c_p g} \frac{g}{c} J \]

(24) Calculate acoustic speed in gas phase.

\[ a_{g_2} = \left( \gamma R T_{g_2} g_c \right)^{0.5} \]

(25) Assume \( \rho_{g_2} = \rho_{g_1} \) and calculate the acoustic speed in the mixture, \( a_2 \).

(26) Calculate absolute and relative Mach numbers at rotor outlet.

\[ M_2 = \frac{V_2}{a_2} \]

\[ M_{r_2} = \frac{W_2}{a_2} \]

(27) Calculate total pressure loss factor across rotor.

\[ \frac{P_{o_2,r}}{P_{o_1,r}} = \frac{P_{o_2,r_i}}{P_{o_1,r_i}} - \left( \frac{\omega_{g,R} + \omega_{8,R} + \omega_{S,R}}{\omega_{g,R}} \right) \cdot \left( 1 - \frac{p_1}{p_{o_1,r}} \right) \]

(28) Calculate total pressure ratio across rotor, and total and static pressures at rotor outlet.

\[ \frac{P_{o_2}}{P_{o_1}} = \left( \frac{T_{o_2,g}}{T_{o_1,g}} \right)^{\frac{\gamma}{\gamma-1}} \cdot \left( \frac{P_{o_2,r_i}}{P_{o_1,r_i}} \right) \cdot \left( \frac{P_{o_2,r_i}^{-1}}{P_{o_1,r_i}^{-1}} \right) \]

\[ P_{o_2} = \left( \frac{P_{o_2}}{P_{o_1}} \right) P_{o_1} \]

\[ P_{o_2} = (1 + \frac{\gamma - 1}{2} M_2^2) \frac{-\gamma}{\gamma-1} P_{o_2} \]

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(29) Calculate static density at rotor outlet.

\[ \rho_{g2} = \frac{p_2}{R_g T_{g2}} \]

(30) Compare the calculated value of \( \rho_{g2} \) in (29) with the assumed value of \( \rho_{g2} \) in (25). Iterate steps (25) to (29) until a desired accuracy is obtained.

(31) Calculate the density of mixture at rotor outlet.

\[ \rho_{m2} = \left( \frac{x_g}{\rho_{g2}} + \frac{x_w}{\rho_w} \right)^{-1} \]

(32) Calculate the axial velocity at rotor outlet.

\[ V_{Z2} = \frac{\dot{m}}{\rho_{m2} A} \]

(33) Compare the calculated value of \( V_{Z2} \) in (32) with the assumed value of \( V_{Z2} \) in (17). Iterate steps (17) to (32) until a desired accuracy is obtained.

(34) Calculate total pressure at rotor outlet.

\[ P_{02} = \left\{ 1 + \left( \gamma - 1 \right) \frac{M_2^2}{2} \right\} \frac{\gamma}{(\gamma - 1)} p_2 \]

(35) Calculate the total pressure loss coefficient across stator due to gas phase, \( \overline{\omega}_{g,S} \), and stator outlet angle, \( \alpha_3 \).

(36) Obtain the total pressure loss coefficient due to the increase of momentum thickness because of the existence of small droplets in the boundary layer on a stator blade surface, \( \overline{\omega}_{d,S} \).
(37) Obtain the total pressure loss across stator due to the Stokesian drag of water droplets in the free stream outside boundary layer $\bar{\omega}_{S,S}$. It may be noted that Stokesian drag is zero in the case of small droplets by definition.

(38) Calculate total pressure loss factor across stator.

$$\frac{P_{0,3}}{P_{0,2}} = 1 - (\bar{\omega}_{g,S} + \bar{\omega}_{b,S} + \bar{\omega}_{s,S}) \left(1 - \frac{P_2}{P_{0,2}} \right)$$

(39) Calculate the total pressure ratio and gas phase total temperature ratio across stage.

$$PR = \frac{P_{0,3}}{P_{0,1}} = \left( \frac{T_{0,3,g}}{T_{0,1,g}} \right)^{\gamma - 1} \left( \frac{P_{0,2,r}}{P_{0,1,r}} \right) \left( \frac{P_{0,2,r}}{P_{0,1,r}} \right)^{-1} \left( \frac{P_{0,3}}{P_{0,2}} \right)$$

$$TR = \frac{T_{0,3,g}}{T_{0,1,g}}$$

(40) Obtain total pressure and gas phase total temperature at stator outlet.

$$P_{0,3} = \left( \frac{P_{0,3}}{P_{0,2}} \right) P_{0,2}$$

$$T_{0,3,g} = T_{0,2,g}$$

(41) Calculate the average value of specific heat ratio.

(42) Calculate the stage efficiency.

$$n = \frac{PR(\gamma - 1)/\gamma - 1}{TR - 1}$$
A.2.3 Procedure when Large or Large and Small Droplets are Present

It is postulated that when large droplets are present, they always play the more dominant role.

The following assumptions are introduced.

(1) Droplets move with equal probability in all directions in the forward sector.

(2) A fraction of the droplets impacting the droplets undergo rebound. The balance of impacting droplets move over the blade surface in the form of a thick film. The momentum of the thick film is appreciable and represents a loss of mixture momentum.

(3) The development of the boundary layer can be estimated based on the following reasoning: (a) The thick film presents a continuous rough surface; (b) the roughness is at most of the order of droplet thickness; and (c) the boundary layer is fully turbulent and extends over the chord length. A coefficient of friction for the flow can then be based on Ref. 26.

(4) The deviation angle remains the same as in the case of single phase flow.

(5) Considering a blade passage flow, between two neighboring blades, away from solid boundaries, the drag due to droplets can be calculated assuming Stokes drag relation. The number of droplets suffering such drag is the sum of the number of non-impacting droplets and the number of rebound droplets.

(6) The overall loss is therefore obtained by adding the losses described under (2), (3) and (5).

It may be observed that the foregoing procedure for large droplets precludes the use of available stage characteristics and subsequent correction of efficiency due to the presence of droplets. The procedure is also different from the Lieblein analytical/correlation method used in the case of small droplets in that no simple superposition of blade
profile losses is feasible in the case of large droplets. The loss due to Stokesian drag of large droplets in the free stream, of course, is accounted for by simple addition to other losses.

A.2.3.1. Details of Procedure

The stage performance, when large droplets are present, with or without small droplets, is carried out as follows. It may be pointed out that the determination of stage pressure ratio follows the same procedure as in the case of a mixture with small droplets only, Appendix Section A.2.2.2. The determination of the loss coefficient when large droplets are present is wholly different.

1. From given initial conditions or from the previous stage properties the gas phase total temperature, $T_{01, g}$ and total pressure, $P_{01}$, are obtained.

2. Calculate the gas constant, $R_g$, specific heat at constant pressure, $c_{pg}$, and specific heat ratio, $\gamma$.

3. Calculate the stagnation density of gas phase,

$$\rho_{01, g} = \frac{P_{01}}{R_g T_{01, g}}$$

4. Assume a value for Mach number, $M_a$.

5. Calculate the static density, and temperature of gas phase, as follows,

$$\rho_1 = \left(1 + (\gamma - 1)M_a^2/2\right)^{-1/(\gamma - 1)} \cdot \rho_{01, g}$$

$$T_{g1} = \left(1 + (\gamma - 1)M_a^2/2\right)^{-1} \cdot T_{01, g}$$
(6) Calculate the acoustic speed in the gas phase, \( a_{g1} \).
\[
a_{g1} = (\gamma R_g T g l g_c)^{0.5}
\]

(7) Calculate the acoustic speed in the mixture, \( a_1 \).

(8) Calculate the density of the mixture.
\[
\rho_m = \left( \frac{x_g}{\rho_g} + \frac{x_w}{\rho_w} \right)^{-1}
\]

(9) Calculate the axial velocity.
\[
V_{z1} = \frac{\dot{m}_m}{\rho_m A}
\]

(10) Calculate the absolute velocity.
\[
V_1 = \frac{V_{z1}}{\cos \alpha_1}
\]

(11) Calculate the Mach number, \( M_c \).
\[
M_c = \frac{V_1}{a_1}
\]

(12) Compare the assumed Mach number, \( M_a \), with the calculated one, \( M_c \). If \( M_a \) agrees within prescribed limits with \( M_c \), proceed to the next step. Otherwise steps (4) to (11) must be repeated.

(13) Calculate the components of velocity at rotor inlet as follows:
\[
V_1 = \frac{V_{z1}}{\cos \alpha_1}
\]
\[
V_{\theta_1} = \frac{V_{z1}}{\sin \alpha_1}
\]
\( W_{b1} = U_1 - V_{b1} \)

\( W_1 = (V_{z1}^2 + W_{b1}^2)^{1/2} \)

\( B_1 = \tan^{-1}(W_{b1}/V_{z1}) \)

(14) Calculate relative Mach number at rotor inlet.

\( M_{r1} = \frac{W_1}{a_1} \)

(15) Calculate static pressure at rotor inlet.

\[ p_1 = \left\{ \left( \frac{T_{01}}{T_0} \left( \frac{g}{g_T} \right) \right)^{\gamma/(\gamma - 1)} \right\} A_y - 1 \cdot P_{01} \]

(16) Calculate total pressure at rotor inlet based on \( M_{r1} \).

\[ P_{01,r} = \left\{ 1 + (\gamma - 1) M_{r1}^2 / 2 \right\}^{\gamma/(\gamma - 1)} \cdot p_1 \]

(17) Assuming \( V_{z2} \), calculate the total pressure loss due to gas phase, \( \omega_{g,R} \), and rotor outlet angle \( B_2 \).

(18) Calculate the total pressure loss coefficient due to the momentum gained by thick water film moving over the rotor blade surface, \( \omega_{f,R} \).

(19) Calculate the total pressure loss coefficient due to turbulent flow of mixture over the rough film surface of rotor blade, \( \omega_{r,R} \).

(20) Calculate the total pressure loss coefficient due to the Stokesian drag of water droplets in rotor passage, \( \omega_{s,R} \).
(21) Calculate the components of velocity diagram at rotor outlets as follows:

\[ W_{\theta 2} = V_{z 2} \tan \beta_2 \]

\[ V_{\theta 2} = U_2 - W_{\theta 2} \]

\[ W_2 = (V_{z 2}^2 + W_{\theta 2}^2)^{0.5} \]

\[ V_2 = (V_{z 2}^2 + V_{\theta 2}^2)^{0.5} \]

\[ \alpha_2 = \tan^{-1}(V_{\theta 2}/V_{z 2}) \]

(22) Calculate the work input.

\[ \Delta h_0 = (U_2 V_{\theta 2} - U_1 V_{\theta 1})/g_c \]

(23) Apportion the energy input in the mixture as described in item (15) of A.2.2.1.

(24) Calculate static temperature of gas phase at rotor outlet.

\[ T_{g 2} = T_{0 2} + g - V_2^2/2c_p g_c \]

(25) Calculate the acoustic speed in gas phase.

\[ a_{g 2} = (\gamma R T_{g 2} g_c)^{0.5} \]

(26) Assume \( \rho_{g 2} = \rho_{g 1} \) and calculate the acoustic speed in the mixture \( a_2 \).

(27) Calculate absolute and relative Mach number at rotor outlet.

\[ M_2 = V_2/a_2 \]

\[ M_{\text{r}2} = W_2/a_2 \]
(28) Calculate total pressure loss factor across rotor.

\[
\frac{P_{02,r}}{P_{01,r}} = \frac{P_{02,r}}{P_{01,r}} - \left( \omega_g R + \omega_f R + \omega_{s,R} + \omega_{s,s} R \right) \cdot \left( 1 - \frac{P_1}{P_{01,r}} \right)
\]

(29) Calculate total pressure ratio across rotor, and total static pressure at rotor outlet.

\[
\frac{P_{02}}{P_{01}} = \left( \frac{P_{02,r}}{P_{01,r}} \right)^{\gamma - 1} \cdot \left( \frac{P_{02,r}}{P_{01,r}} \right)^{1 - \gamma} = \frac{P_{02}}{P_{01}}
\]

\[
P_{02} = \left( \frac{P_{02}}{P_{01}} \right) P_{01}
\]

\[
P_{2} = (1 + \frac{\gamma - 1}{2} M_2^2) \frac{\gamma}{\gamma - 1} P_{02}
\]

(30) Calculate static density at rotor outlet.

\[
\rho_{g2} = \frac{p_2}{R_g T_{g2}}
\]

(31) Compare the calculated \( \rho_{g2} \) in (27) with the assumed \( \rho_{g2} \) in (23). Iterate steps (23) to (27) until a desired accuracy is obtained.

(32) Calculate the density of mixture.

\[
\rho_{m2} = \left( \frac{x_g}{g} + \frac{x_w}{w} \right)^{-1}
\]

(33) Calculate the axial velocity at rotor outlet.

\[
V_{Z2} = \frac{\dot{m}}{\rho_m A_2}
\]
(34) Compare the calculated $V_{z2}$ in (33) with the assumed $V_{z2}$ in (34). Iterate steps (17) to (33) until the desired accuracy is obtained.

(35) Calculate total pressure at rotor outlet.

$$P_{02} = \left\{ 1 + \left( \frac{\gamma - 1}{\gamma - 1} \right)^{\frac{\gamma^2}{2}} \right\} \frac{\gamma}{\gamma - 1} . p_2$$

(36) Calculate the total pressure loss coefficient across stator due to gas phase, $\bar{\omega}_{g,S}$, and stator outlet angle, $\alpha_3$.

(37) Calculate the total pressure loss coefficient due to the momentum gained by thick water film on the stator blade surface, $\bar{\omega}_{f,S}$.

(38) Calculate the total pressure loss coefficient due to turbulent friction over a rough film surface over the stator blade, $\bar{\omega}_{r,S}$.

(39) Obtain the total pressure loss across stator due to Stokesian drag of large water droplets in the free stream outside boundary layer, $\bar{\omega}_{s,S}$.

(40) Calculate total pressure loss factor across the stator.

$$\frac{P_{03}}{P_{02}} = 1 - (\bar{\omega}_{g,S} + \bar{\omega}_{f,S} + \bar{\omega}_{r,S} + \bar{\omega}_{s,S}) (1 - \frac{P_2}{P_{02}})$$

(41) Calculate the total pressure ratio and gas phase total temperature ratio across stage.

$$PR = \frac{P_{03}}{P_{01}} = \left( \frac{T_{03,g}}{T_{01,g}} \right)^{\frac{\gamma - 1}{\gamma}} \cdot \left( \frac{P_{02,g}}{P_{01,r}} \right) \cdot \left( \frac{P_{02,r1}}{P_{01,r}} \right)^{-1} \cdot \left( \frac{P_{03}}{P_{02}} \right)$$

$$TR = \frac{T_{03,g}}{T_{01,g}}$$
(42) Obtain total pressure and gas phase total temperature at stator outlet.

\[ P_{0,3} = \left( \frac{P_{0,3}}{P_{0,2}} \right) \cdot P_{0,2} \]

\[ T_{0,3,g} = T_{0,2,g} \]

(43) Calculate the average value of the specific heat ratio.

(44) Calculate the stage efficiency.

\[ \eta = \frac{P_R(Y-1)/Y-1}{T_R - 1} \]
APPENDIX 3

DETAILED DESCRIPTION OF SUBROUTINES
AND EXTERNAL FUNCTIONS

There are 27 subroutines and 13 external functions in this program. Brief descriptions of these subprograms are presented in Chapter III. A more detailed description of each subprogram is presented here. Each of the subroutines and external functions is presented as follows:
(1) Description, (2) Input variables, (3) Output variables, and (4) Usage.

SUBROUTINE WICSPA

(1) Description:
The subroutine WICSPA is used for the calculation of performance based on the inputed stage characteristic curves. A detailed description of calculation procedure is presented in Appendix 2.

(2) Input Variables:
FAIO initial flow coefficient
ISTAGE stage at which performance calculation is carried out
MMASS mass flow rate of mixture.
ALFA absolute flow angle at outlet of the previous stage stator
WKDONE work done factor
DAVE nominal diameter of small droplet
XDIN initial water content of small droplet
AK1 constant in Eq. (A.3.6)'
AK3 constant in Eqs. (A.3.1)' and (A.3.2)'

(3) Output Variables:
ETA stage adiabatic efficiency
BETA1 relative flow angle at rotor inlet
BETA2 relative flow angle at rotor outlet
VZ axial velocity
ALFA2  absolute flow angle at stator inlet
ALFA3  absolute flow angle at stator outlet
DELTG  rise in total temperature of gas phase across a stage
DELTW  rise in temperature of small droplet across a stage
W1     relative velocity at rotor inlet
W2     relative velocity at rotor outlet
V1     absolute velocity at rotor inlet
V2     absolute velocity at stator inlet
V3     absolute velocity at stator outlet

(4) Usage:

CALL WICSPA (FAIO, ISTAGE, MMASS, ALFA1, WKDONE, DAVE, XDIN ETA, BETA1, BETA2, VZ, ALFA2, ALFA3, DELTG, DELTW, W1, W2, V1, V2, V3, AK1, AK3)

SUBROUTINE WICSPB

(1) Description:
The subroutine WICSPB is used for the calculation of stage performance based on the analytical/correlation method for small droplet. A detailed description of calculation procedure is presented in Appendix 2.

(2) Input Variables:

FAIO     initial flow coefficient
ISTAGE   stage at which performance calculation is carried out
MMASS    mass flow rate of mixture
ALFA1    absolute flow angle at outlet of the previous stage stator
WKDONE   work done factor
DAVE     nominal diameter of small droplets
DELV relative velocity between gas phase and large droplets

XMAS mass flow rate of small droplets

N station number (Fig. 5.1)

AK1 constant in Eq. (A.3.6)'

AK2 constant in Eq. (A.3.7)' and (A.3.8)'

AK3 constant in Eq. (A.3.1)' and (A.3.2)'

\( (3) \) Output Variables:

OMEGA1 total pressure loss coefficient due to single-phase (gas) flow profile loss in rotor

OMEGA2 total pressure loss coefficient due to loss for small droplets on account of the change in momentum thickness of boundary layer due to the presence of such droplets in rotor

OMEGA3 total pressure loss coefficient due to Stokesian drag of small droplets in the free stream of blade passage in rotor

OMEGA4 total pressure loss coefficient due to single-phase (gas) flow profile loss in stator

OMEGA5 total pressure loss coefficient due to loss for small droplets on account of the change in momentum thickness of boundary layer due to the presence of such droplets in stator

OMEGA6 total pressure loss coefficient due to Stokesian drag of small droplets in the free stream of blade passage in stator

OMEGAT sum of total pressure loss coefficients
BETA1  relative flow angle at rotor inlet
BETA2  relative flow angle at rotor outlet
VZ     axial velocity
ALFA2  absolute flow angle at stator inlet
ALFA3  absolute flow angle at stator outlet
DELTG  rise in total temperature of gas phase across a stage
DELTW  rise in temperature of small droplet across a stage
W1     relative velocity at rotor inlet
W2     relative velocity at rotor outlet
V1     absolute velocity at rotor inlet
V2     absolute velocity at stator inlet
V3     absolute velocity at stator outlet

(4) Usage:

CALL WICSPB (FAIO, ISTAGE, M MASS, ALFA1, WKDONE, DAV, DELV, WMAS, N, OMEGA1, OMEGA2, OMEGA3, OMEGA4, OMEGA5, OMEGA6, OMEGAT, BETAI, BETA2, VZ, ALFA2, ALFA3, DELTG, DELTW, W1, W2, V1, V2, V3, AK1, AK2, AK3)
SUBROUTINE WICSPC

(1) Description:

The subroutine WICSPC is used for the calculation of stage performance based on the analytical/correlation method for large droplet. A detailed description of calculation procedure is presented in Appendix 2.

(2) Input Variables:

FAIO initial flow coefficient
ISTAGE stage at which performance calculation is carried out
MMASS mass flow rate of mixture
ALFA1 absolute flow angle at outlet of the previous stage stator
WKDONE work done factor
DAV nominal diameter of large droplets
DELV relative velocity between gas phase and large droplets
WMAS mass flow rate of small droplets
WWMAS mass flow rate of large droplets
N station number (Fig. 5.1)
REAVE Average Reynolds number
DELVU2  relative velocity between gas phase and droplet

DELVL2  relative velocity between gas phase and droplet

AK1  constant in Eq. (A.3.6)'

AK2  constant in Eq. (A.3.7)' and (A.3.8)'

AK3  constant in Eq. (A.3.1)' and (A.3.2)'

(3) Output Variables:

OMEGA1  total pressure loss coefficient due to the mixture boundary layer formed over rough film surface in rotor

OMEGA2  total pressure loss coefficient due to film formed on rotor blade surface

OMEGA3  total pressure loss coefficient due to Stokesian drag of large droplets in the free stream of blade passage in rotor

OMEGA4  total pressure loss coefficient due to the mixture boundary layer formed over rough film surface in stator

OMEGA5  total pressure loss coefficient due to film formed on stator blade surface

OMEGA6  total pressure loss coefficient due to Stokesian drag of large droplets in the free stream of blade passage in stator
OMEGAT  sum of total pressure loss coefficient

BETAI  relative flow angle at rotor inlet

BETA2  relative flow angle at rotor outlet

VZ    axial velocity

ALFA2  absolute flow angle at stator inlet

ALFA3  absolute flow angle at stator outlet

DELTG  rise in total temperature of gas phase across a stage

DELTW  rise in temperature of small droplet across a stage

W1    relative velocity at rotor inlet

W2    relative velocity at rotor outlet

V1    absolute velocity at rotor inlet

V2    absolute velocity at stator inlet

V3    absolute velocity at stator outlet

(4) Usage:

CALL WICSPC (FAIO, ISTAGE, MMASS, ALFA1, WKDONE, DAV, DELV, WMAS, WMAS, N, OMEGA1, OMEGA2, OMEGA3, OMEGA4, OMEGA5, OMEGA6, OMEGA7, BETA1, BETA2, VZ, ALFA2, ALFA3, DELTG, DELTW, W1, W2, V1, V2, V3, REAVE, DELVU2, DELVL2, AK1, AK2, AK3)
SUBROUTINE WICSPD

(1) Description

The subroutine WICSPD is used for the calculation of design point performance. The properties obtained in this subroutine become reference properties for calculation of off-design performance.

(2) Input Variables

AMASS mass flow rate

ISTAGE stage at which performance calculation is carried out

(3) Output Variables:

none

(4) Usage:

CALL WICSPD (AMASS, ISTAGE)
SUBROUTINE WICSCC

(1) Description:

Subroutine WICSCC calculates the equivalent pressure ratio, stage adiabatic efficiency, and equivalent temperature ratio for a particular stage from the inputted stage characteristic curves. The equivalent pressure ratio, $\psi$, equivalent temperature ratio, $\tau$, and stage adiabatic efficiency, $\eta$, have been expressed in terms of the stage flow coefficient as follows:

\[ \psi = A_1 + B_1 \phi + C_1 \phi^2 + D_1 \phi^3 + E_1 \phi^4 + F_1 \phi^5 + G_1 \phi^6 \]

\[ \eta = A_2 + B_2 \phi + C_2 \phi^2 + D_2 \phi^3 + E_2 \phi^4 + F_2 \phi^5 + G_2 \phi \]

\[ \tau = A_3 \phi + B_3 \]

The definitions of these parameters are as follows:

(i) flow coefficient: $\phi$

\[ \phi = \frac{V_z}{U_{tip}} \]

(ii) equivalent pressure ratio $\psi$

\[ \psi = \left( \frac{U_{tip}^2}{T_{tip}} \right)_D \left( \frac{T_{tip}}{U_{tip}^2} \right) \left[ \frac{P_{D2}}{P_{D1}} \right]^{(\gamma-1)/\gamma} - 1 + 1 \]

(iii) equivalent temperature ratio:

\[ \tau = \left( \frac{U_{tip}^2}{T_{tip}} \right)_D \left( \frac{\Delta T_0}{U_{tip}^2} \right) \]

where subscript $D$ indicates the design point.
It should be noted here that the subroutine WICSCC is only suitable for the case of Test Compressor employed in the current investigation. In another case, a replacement of this subroutine is necessary.

(2) Input Variables:

FAI stage flow coefficient
ISTAGE stage number

(3) Output Variables:

SAI equivalent pressure ratio
ETA stage adiabatic efficiency
TAU equivalent temperature ratio

(4) Usage:

CALL WICSP (FAI, SAI, ETA, TAU, ISTAGE)

SUBROUTINE WICGSL

(1) Description:

The subroutine WICGSL is used for the calculation of single-phase (gas) flow loss. In the current model, the concept of the equivalent diffusion ratio by Lieblein (Ref.23) and Swan's correlation (Ref.24) have been employed in order to estimate the blade outlet flow angle and loss due to turbulent flow of gaseous phase over the rigid blade surface.

Lieblein has show that the design point loading factor, the Diffusion Factor, does not represent a suitable criterion for loading at off-design conditions, except possibly at
other minimum loss points. This is due to the fact that the basic derivation of the Diffusion Factor has been based on a flow model which corresponds to operation at or near minimum loss. He has therefore suggested a generalized loading parameter. This parameter, the Equivalent Diffusion Ratio, is based on the ratio of the maximum suction surface velocity and trailing edge velocity for a given section cascade. Lieblein has deduced an expression which approximates this velocity ratio in terms of measured overall performance. The Equivalent Diffusion Ratio is suitable for correlation of low speed data. For the general case where the axial velocity ratio may be large, such as in a rotor or stator cascade, the Equivalent Diffusion Ratio, \( D_{eq} \), has been defined as follows:

\[
D_{eq} = \frac{\cos \beta_2 V_{z_1}}{\cos \beta_1 V_{z_2}} \left[ 1.12 + k (i-i^*)^{1.43} + 0.61 \frac{\cos^2 \beta_1}{\sigma} \cdot K \right] \quad (A.3.1)
\]

where \( K = \tan \beta_1 - \frac{r_2}{r_1} \frac{V_{z_2}}{V_{z_1}} \tan \beta_2 - \frac{\omega r_1}{V_{z_1}} \left( 1 - \frac{r^2}{r_1^2} \right) \)

and \( k = 0.0117 \) for the NACA 65 \((A_{10})\) blades and \( k = 0.007 \) for the C4 circular-arc blades. The Equivalent Diffusion Ratio at minimum loss, \( D_{eq^*} \), is obtained by dropping the term representing the incidence angle effects, that is as follows.

\[
D_{eq^*} = \frac{\cos \beta_2 V_{z_1}}{\cos \beta_1 V_{z_2}} \left[ 1.12 + 0.61 \frac{\cos^2 \beta_1}{\sigma} \cdot K \right] \quad (A.3.2)
\]

The wake momentum thickness can be expressed nondimensionally as follows:

\[
\frac{\bar{\alpha}}{c} = \frac{\omega \cos \beta_2}{2 \sigma} \left( \frac{\cos \beta_1}{\cos \beta_2} \right)^2 \quad (A.3.3)
\]

where \( c \) is the chord length of the blades.
At minimum loss, Eq. (A.3.3) yields

\[ \frac{\theta}{c} = \frac{\bar{\omega} \cos \beta_2}{2\alpha} \left( \frac{\cos \beta_2}{\cos \beta_1} \right) \]  \hspace{1cm} (A.3.4)

Also, from Eq. (A.3.3), the total pressure loss coefficient \( \bar{\omega} \), can be expressed as follows:

\[ \bar{\omega} = \left( \frac{\theta}{c} \right) \frac{2\alpha}{\cos \beta_2} \left( \frac{\cos \beta_1}{\cos \beta_2} \right)^2 \]  \hspace{1cm} (A.3.5)

From the cascade test data, the deviation angle, \( \delta \), and the non-dimensional wake momentum thickness, \( \frac{\theta}{c} \), are expressed in terms of the \( D_{eq} \), \( D_{eq}^* \), \( \left( \frac{\theta}{c} \right)^* \), and inlet Mach number, \( M \), as follows:

\[ \delta = \delta^* + \left[ 6.40 - 9.45(M_1 - 0.60) \right] (D_{eq} - D_{eq}^*) \]. \hspace{1cm} (A.3.6)

\[ \frac{\theta}{c} = \left( \frac{\theta}{c} \right)^* + \left( 0.827M_1 - 2.692M_1^2 - 2.675M_1^3 \right) (D_{eq} - D_{eq}^*)^2 \]. \hspace{1cm} (A.3.7)

\[ \frac{\theta}{c} = \left( \frac{\theta}{c} \right)^* + \left( 2.80M_1 - 8.71M_1^2 + 9.36M_1^3 \right) (D_{eq} - D_{eq}^*)^2 \]. \hspace{1cm} (A.3.8)

Using these empirical expressions, the air angle at blade outlet and total pressure loss coefficient at an off-design point can be determined as follows:

(i) Calculate the inlet angle, \( \beta_1 \), and the inlet Mach number, \( M_1 \).

(ii) Calculate the Equivalent Diffusion ratio at minimum loss, \( D_{eq}^* \).
(iii) Calculate the nondimensional wake momentum thickness at minimum loss, \( \left( \frac{\theta}{C} \right)_* \).

(iv) Assume the fluid outlet angle, \( \beta_2 \)\(_a\).

(v) Calculate the incidence angle, \( i \), \( i = \beta_1 - \beta_2*+i* \).

(vi) Calculate the Equivalent Diffusion Ration \( D_{eq} \).

(vii) Calculate the deviation angle, \( \delta \).

(viii) Calculate the fluid outlet angle, \( \beta_2 \)\(_c\), \( \beta_2\)\(_c\) = \( \beta_2* - \delta* + \delta \).

(ix) Compare the assumed value of fluid outlet angle, \( \beta_2 \)\(_a\), with the calculated value of that, \( \beta_2 \)\(_c\) to check if \(|(\beta_2 \)\(_a\) - (\beta_2 \)\(_c\)| < \( \varepsilon \) where \( \varepsilon \) is the desired accuracy. Iterate step (iv) to step (ix) until satisfactory accuracy is obtained.

(x) Calculate the nondimensional wake momentum thickness, \( \frac{\theta}{C} \).

(xi) Calculate the total pressure loss coefficient \( \omega \).

Figure (A.3.1) shows the flow chart of the calculation procedure to predict the outlet angle and total pressure loss coefficient.

The program also includes a provision for modifying the equations given in Ref.23 and 24. Equations (A.3.1), (A.3.2), (A.3.6), (A.3.7), and (A.3.8) can be modified by introducing constants AK1, AK2, and AK3 as follows.
Calculate $M_1$ and $\beta_1$

Calculate $D_{eq}$ and $(\frac{2}{c})^*$

Assume $(\beta_2)_a$

Calculate $D_{eq}$ and $\delta$

Calculate $(\beta_2)_c$

If $|{(\beta_2)_a} - {(\beta_2)_c}| < \epsilon$

Calculate $(\frac{\beta}{c})$

Calculate $\bar{\omega}$

Fig. A.3.1 Procedure for Prediction of Total Pressure Loss Coefficient
\[ D_{eq} = \frac{\cos \beta_2}{\cos \beta_1} \frac{V_{z1}}{V_{z2}} \left[ 1.12 + k (1 - 1.43 (1 - i^*)) + 0.61 \frac{\cos^2 \beta}{\alpha} \right] \cdot AK3 \] (A.3.1)'

\[ D^*_{eq} = \frac{\cos \beta_2}{\cos \beta_1} \frac{V_{z1}}{V_{z2}} \left[ 1.12 + 0.61 \frac{\cos^2 \beta}{\alpha} \right] \cdot AK3 \] (A.3.2)'

\[ \alpha = \alpha^* + \left[ 6.40 - 9.45 (M_2 - 0.60) \right] (D_{eq} - D_{eq}^*) \cdot AK1 \] (A.3.6)'

\[ \frac{\theta}{c} = \left( \frac{\theta}{c} \right)^* + (0.827M_1 - 2.692M_1^2 - 2.695M_1^3) (D_{eq} - D_{eq}^*)^2 \cdot AK2 \] for \( D_{eq} > D_{eq}^* \) (A.3.7)'

\[ \frac{\theta}{c} = \left( \frac{\theta}{c} \right)^* + (2.80M_1 - 8.71M_1^2 + 9.36M_1^3) (D_{eq} - D_{eq}^*)^2 \cdot AK2 \] for \( D_{eq} < D_{eq}^* \) (A.3.8)'

(2) Input Variables:

OMEGAS total pressure loss coefficient

SIGUMA solidity

BETA1S blade inlet flow angle at design point

BETA2S blade outlet flow angle at design point

AINCIS incidence at design point

ADEVIS deviation at design point

AMACH1 blade inlet Mach number

BET1 blade inlet flow angle
X  Mach number below which the effect of Mach
number disappears in estimating deviation
angle. The value of 0.6 is recommended by
Swan (Ref.24).

IDESIN  Index for design point calculation

AK1  constant in Eq.(A.3.6)'

AK2  constant in Eq.(A.3.7)' and (A.3.8)'

AK3  constant in Eq.(A.3.1)' and (A.3.2)'

VZ1  axial velocity at blade inlet

VZ2  axial velocity at blade outlet

UR1  rotor blade speed at blade inlet

R1  radius at blade inlet

R2  radius at blade outlet

(3) Output Variables:

DEQS  equivalent diffusion ratio at design point, $D_{eq}^*$

DEQN  equivalent diffusion ratio, $D_{eq}$

SITACS  dimensionless momentum thickness at design
point, $(\theta/\tau)^*$

SITACN  dimensionless momentum thickness, $(\theta/\tau)$

BET2N  blade outlet angle

OMEGAN  total pressure loss coefficient
CALL WICGSL(OMEGAS, SIGUMA, BET1S, BET2S, AINCIS, ADEVIS, AMACH1, BET1, DEQS, DEQN, SITACS, SITACN, BET2N, OMEGAN, X IDESIN, AK1, AK2, AK3, VZ1, VZ2, UR1, R1, R2)

**SUBROUTINE WICSDL**

(1) **Description:**

The subroutine WICSDL is used for the calculation of loss for small droplets on account of the change in momentum thickness of boundary layer due to the presence of such droplets.

In order to estimate the loss pertaining to the increase of momentum thickness due to the existence of small droplets in the boundary layer, Soo's boundary layer analysis for a gas-solids suspension is introduced (Ref. 25). In an isothermal incompressible system, Soo has derived the following equation for suspended particles under the assumption that the number of collisions among particles is negligible when compared to that with the wall,

\[
a = \left( \frac{a}{b} \right) \left( \frac{\delta}{x} \right) + \frac{4a^2}{3b^2} \left( \frac{\delta}{x} \right) \frac{5}{6} + \frac{4a^3}{3b^3} \left( \frac{\delta}{x} \right) \frac{1}{2} - \frac{4a^4}{b} \left( \frac{\delta}{x} \right) \frac{1}{4} \\
+ \frac{4a^5}{b^3} \ln \left[ 1 + \frac{b}{a} \left( \frac{\delta}{x} \right)^{1/4} \right]
\]

(A.3.9)

where

\[
a = \frac{0.0225 \left( \frac{\bar{u}}{\bar{u}_p} \right)^{1/4}}{0.1402 \left( \frac{\rho}{\rho_0} \right) + 0.0972}
\]
Neglecting shear due to impact of solid particles, Soo derived the following equation.

\[
\frac{\delta}{X} = 0.37 \left( \frac{U_X a}{\mu} \right)^{-1/5} \left( 1 + 1.442 \frac{\rho_p}{\rho_0} \right)^{0.8} \quad (A.3.10)
\]

The boundary layer thickness, \( \delta \), can be obtained from Eqs. (A.3.9) or (A.3.10). In the present model, Eq. (A.3.10) was used.

The momentum thickness, due to liquid phase, \( \theta_p \), is given by

\[
\frac{\theta_p}{\delta} = \left( \frac{U_p - U_{pw}}{U_p} \right)^2 \left( 1 + m \right) \left( 2 + m \right) - \left( \frac{\rho_p - \rho_{pw}}{\rho_p} \right) \cdot \frac{U_{pw}}{U_p} \cdot \frac{1}{\alpha + 1}
\]

\[
+ \left( \frac{\rho_p - \rho_{pw}}{\rho_p} \right) \left( \frac{U_p - U_{pw}}{U_p} \right)^2
\]

\[
x \left[ \frac{\left( \frac{1}{m} + 1 \right) \cdot r(\alpha + 1) - r(\frac{1}{m} + 1) \cdot r(\alpha + 1)}{r\left( \frac{2}{m} + \alpha + 2 \right) - r\left( \frac{1}{m} + \alpha + 2 \right)} \right]
\]

\[(A.3.10)\]

where \( \alpha \) and \( m \) are constants associated with distribution of velocity and density of liquid phase in the boundary layer namely

\[
u_p = u_{pw} + (U_p - U_{pw}) (\frac{\chi}{\delta})^{1/m}
\]

\[
\rho_p = \rho_{pw} - (\rho_p - \rho_{pw}) (1 - \frac{\chi}{\delta})^\alpha
\]

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For the case of solid, spherical particles of 100 and 200\(\mu m\) in diameter in air moving at room conditions with a velocity of 50 to 100 fps, Soo has obtained the following values for the various quantities.

\[ n = 7, \quad m = 1.25, \quad \alpha = 2.30, \]

\[ \frac{U_p - U_{pw}}{U_p} = 0.812, \quad \frac{\rho_{pw}}{\rho_{p0}} = 1.451 \]

Utilizing the above values, Eq. (A.3.10) becomes

\[ \frac{\theta_p}{\theta} = 0.1402 \]

Following the procedure of Lieblein, the total pressure loss coefficient due to the increase of momentum thickness, \(\theta_{p,R}\), because of the existence of small droplets in the boundary layer over rotor blade surface, \(\bar{\omega}_\theta,R\), can be expressed as follows:

\[ \omega_{\theta,R} = \left( \frac{\theta_{p,R}}{c} \right) \frac{2 \sigma}{\cos \beta_2} \left( \frac{\cos \beta_1}{\cos \beta_2} \right)^2 \]

Similarly, the total pressure loss coefficient due to the increase of momentum thickness, \(\theta_{p,S}\), because of the existence of small droplets in the boundary layer on stator blade surface \(\bar{\omega}_\theta,S\), can be expressed as follows:

\[ \omega_{\theta,S} = \left( \frac{\theta_{p,S}}{c} \right) \frac{2 \sigma}{\cos \alpha_3} \left( \frac{\cos \alpha_2}{\cos \alpha_3} \right)^2 \]
The stagnation pressure losses corresponding to $\bar{\omega}_\theta$,r and $\bar{\omega}_\theta$,S can be written as follows.

$$\Delta P_{\theta,R} = \frac{1}{2} \rho_1 \bar{W}_1^2 \bar{\omega}_\theta, R$$

$$\Delta P_{\theta,S} = \frac{1}{2} \rho_1 \bar{V}_2^2 \bar{\omega}_\theta, S$$

Thus, the total pressure loss across a stage due to the increase of momentum thickness because of the existence of small droplets in a boundary layer is given by

$$\Delta P_{\theta} = \Delta P_{\theta,R} + \Delta P_{\theta,S}$$

(2) Input Variables

CHORD chord length
SIGUMA solidity
BETA1 blade inlet flow angle
BETA2 blade outlet flow angle
UG average flow velocity
RHOG density
AMASSW mass flow rate
AREA flow area
VZ axial velocity
IPRINT index for printout

(3) Output Variables:

OMEGAP total pressure loss coefficient
SUBROUTINE WICSTL

(1) Description:

The subroutine WICSTL is used for the calculation of loss due to Stokesian drag of droplets in the free stream of blade passage.

In view of the assumption pertaining to motion of small droplets (with zero relative velocity with respect to gas phase), the total pressure loss due to Stokesian drag becomes zero for small droplets.

For large droplets, the model introduced is described below.

The large droplets move with substantial relative velocity with respect to the gas phase and have equal probability of motion in all directions. However, regarding the latter aspect, the droplets are divided into two subclasses with a direction of motion for each class, specified with respect to the gas phase velocity vector. The number of droplets impacting on the blade surface is then proportional to the blade surface area projection normal to the velocity vectors for the two subclasses of droplets.

Referring to Fig. A.3.2., the two subclasses are shown as (1) and (2) which have direction of motion given by \( \gamma_1 \) and \( \gamma_2 \) relative to the gas phase velocity vector. The total number of droplets in subclass (1) is proportional to angle \( 2\gamma_1 \) and those in subclass (2) is proportional to angle \( 2\gamma_2 \) \((180 - 2\gamma_1)\). The relative velocity between the gas phase and droplets of subclass (1) is given by the difference between \( V \) and the component of \( V_p \) (the velocity of drop-
Fig. A.3.2 Model for Motion of Large Droplet
lets in subclass (1) in the direction of \( V_{g1} \). Similarly
the relative velocity between the gas phase and the droplets
of subclass (2) is given by the difference between \( V_{g1} \)
and the component of \( V_{p2} \) in the direction of \( V_{g1} \). Thus
for droplets of subclass (1) the relative velocity is
given by the relation,

\[
V_{g1} - V_{p1} \cos \gamma_1
\]

and for droplets of subclass (2), the relative velocity is
given by the relation,

\[
V_{g1} - V_{p2} \cos \gamma_2
\]

In Fig. A.3.2, the blade outlet conditions are also shown.
As at the blade inlet section the relative velocities between
the gas phase and droplets of subclasses (1) and (2) may
be written as follows:

\[
V_{g2} - V_{p1} \cos \delta_1 \quad \text{for subclass (1), and}
\]

\[
V_{g2} - V_{p2} \cos \delta_2 \quad \text{for subclass (2).}
\]

where \( \delta_1 \) is the inclination of the mean velocity vector for
subclass (1) and \( \delta_2 \), the inclination of the mean velocity
vector at outlet, designated \( V_{g2} \). Once again, at the outlet
section, the number of droplets in subclass (1) is
proportional to angle \( 2\delta_1 \), and the number of droplets in
subclass (2) is proportional to angle \( 2\delta_2 \), or \((180-2\delta_1)\).
It is clear that the total number of droplets is divided
into two new subclasses at the outlet, based on the directions
of motion of droplets relative to the gas phase velocity.
The two subclasses at the outlet are the output from the
blade row for the given initial and operating conditions.
Based on the foregoing model of motion of large droplets the total pressure loss coefficient due to the Stokesian drag of large water droplets in a rotor passage, $\omega_{s,R}$, can be estimated as follows:

The Stokesian drag of water droplets across a rotor blade is given by

$$D = \frac{1}{D^2} \rho g_1 (W_{g1} - W_{p1})^2 A_p N_{d,R}$$

Where $W_{g1}$ and $W_{p1}$ are relative velocities of gaseous phase and droplets at rotor inlet, $A_p$, the project area of a droplet, and $N_{d,R}$, the number of droplets that exist in rotor passage. Referring to Fig. A.3.3, the Stokesian drag, $D$, can also be written as

$$D = (P_{01,R} - P_{02,R}) A_R$$

where $P_{01,R}$ and $P_{02,R}$ are total pressure at station (1) and (2) in rotor coordinate system, and $A_R$ is the average flow area in a rotor blade passage.

From the above equations, the total pressure loss across a rotor blade due to the Stokesian drag, $\Delta P_{s,R}$ becomes

$$P_{s,R} = c_D \frac{1}{2} \rho g_1 (W_{g1} - W_{p1})^2 A_p N_{d,R}/A_R = D/A_R$$

By definition, the total pressure loss coefficient across a rotor blade due to Stokesian drag, $\omega_{s,R}$, can be obtained as follows:

$$\omega_{s,R} = \frac{\Delta P_{s,R}}{\Delta P_{g1} W_{g1}^2} = c_D (W_{g1} - W_{p1})^2 A_p N_{d,R}/W_{g1}^2 A_R = \frac{D/A_R}{\frac{\Delta P_{g1} W_{g1}^2}{g_1}}$$
Fig. A.3.3  Control Volume across a Blade
Similarly, the total pressure loss across a stator blade due to Stokesian drag, $\Delta P_{s,S}$ becomes

$$\Delta P_{s,S} = c_D \frac{1}{2} \rho g_{2} (V_{g_{2}} - V_{p_{2}}) A N_{d,S} / A_{S}$$

and the total pressure loss coefficient across a stator blade due to the Stokesian drag, $\omega_{s,S}$, can be obtained as follows:

$$\omega_{s,S} = \frac{\Delta P_{s,S}}{\rho g_{2} V_{2}^2} = c_D (V_{g_{2}} - V_{p_{2}}) A N_{d,S} / A_{S}$$

Thus, the total pressure loss across a stage due to Stokesian drag is given by

$$\Delta P_{S} = \Delta P_{s,R} + \Delta P_{s,S}$$

(2) Input Variables:

- **ISTAGE**: stage at which performance calculation is carried out
- **IROTOR**: index for rotor or stator
- **DAV**: nominal droplet diameter
- **W1**: relative velocity at rotor inlet
- **W2**: relative velocity at rotor outlet
- **DELV**: relative velocity between gas phase and droplet
- **V2**: absolute velocity at stator inlet
- **V3**: absolute velocity at stator outlet
- **WMASS**: mass flow rate of droplet
- **VZ**: axial velocity
- **N**: station number (Fig. 5.1)
- **BETA1**: relative flow angle at rotor inlet
- **BETA2**: relative flow angle at rotor outlet
ALFA2  absolute flow angle at stator inlet
ALFA3  absolute flow angle at stator outlet
MMASS  mass flow rate of mixture

Output Variables:

DELVU2  relative velocity between gas phase and large droplet in subclass (1) at blade outlet
DELVL2  relative velocity between gas phase and large droplet in subclass (2) at blade outlet
OMEGRU  total pressure loss coefficient across rotor due to Stokesian drag in subclass (1)
OMEGRL  total pressure loss coefficient across rotor due to Stokesian drag in subclass (2)
OMEGSU  total pressure loss coefficient across stator due to Stokesian drag in subclass (1)
OMEGSL  total pressure loss coefficient across stator due to Stokesian drag in subclass (2)
DRAGRU  drag force due to large droplet in subclass (1)
DRAGRL  drag force due to large droplet in subclass (2)
DRAGSU  drag force due to small droplet in subclass (1)
DRAGSL  drag force due to small droplet in subclass (2)
REAVE  average Reynolds number

Usage:

CALL WICSTL (ISTAGE, IROTOR, DAV, WI, W2, DELV, V2, V3, 
WMMASS, VZ, N, BETA1, BETA2, ALFA2, ALFA3, 
MMASS, DELVU2, DELVL2, OMEGRU, OMEGRL, OMEGSU, 
OMEGSL, DRAGRU, DRAGRL, DRAGSU, DRAGSL, REAVE)
SUBROUTINE WICFML

(1) Description:

The subroutine WICFML is used for the calculation of loss due to film formed on blade surface when large droplets are present either by themselves or along with small droplets.

The momentum gained by the thick water film on the rotor blade surface is given by \( \dot{m}_{film} V_{film} \) per unit blade length, where \( \dot{m}_{film} \) is the mass flow rate of water film on the rotor blade per unit blade length and \( V_{film} \) is the mean velocity of water film.

Considering the difference in viscosity between the two phases, the velocity of water film can be estimated as follows:

\[
V_{film} = \frac{1}{2} \frac{\bar{W}}{g} \frac{\mu_g}{\mu_l}
\]

where \( \bar{W} \) is the mean velocity of gaseous phase, and \( \mu_g \) and \( \mu_l \) are the viscosities of gaseous and liquid phases, respectively.

The foregoing momentum can be transformed into an equivalent drag coefficient as follows.

\[
c_{Df} = \frac{\dot{m}_{film} V_{film}}{2 \rho_{g1} \bar{W}^2 c}
\]

where \( \rho_{g1} \) is blade inlet density of gaseous phase, and \( c \) is the chord length of the blade.

The drag coefficient can then be expressed in the form of a total pressure loss coefficient as follows:

\[
c_{Df} = \frac{1}{2} \rho_{g1} \bar{W}^2 c = \Delta P_f . s . \cos \beta_m
\]

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where \( s \) is the blade pitch and \( \beta_m \) is mean flow angle.

Noting that \( V_z = \bar{W}_g \cos \beta_m \), one obtains the relation, namely

\[
\frac{1}{2} \frac{\Delta P_f}{\frac{1}{2} \rho g_1 V_z^2} = C_{D_f} \left( \frac{L}{s} \right) \frac{1}{\cos^3 \beta_m}
\]

Since \( \bar{W}_g = V_z / \cos \beta_1 \), the total pressure loss coefficient due to the momentum gained by the thick film on the rotor blade surface can be written as follows:

\[
\frac{\bar{W}_g}{\omega_f} = \frac{1}{2} \frac{\Delta P_f}{\frac{1}{2} \rho g_1 \bar{W}_g^2} = C_{D_f} \left( \frac{L}{s} \right) \frac{\cos^2 \beta_1}{\cos^3 \beta_m}
\]

(2) Input Variables:

- \( Wg1 \): flow velocity at blade inlet
- \( Wg2 \): flow velocity at blade outlet
- \( FMASS \): mass flow rate of water film on blade surface per unit blade length
- \( RHOG1 \): density
- \( CHORD \): chord length
- \( SIGUMA \): solidity
- \( BETA1 \): blade inlet flow angle
- \( BETA2 \): blade outlet flow angle

(3) Output Variables:

- \( CDF \): drag coefficient
- \( OMEGAF \): total pressure loss coefficient

(4) Usage:

CALL WICFML (WG1, WG2, FMASS, RHOG1, CHORD, SIGUMA, BETA1, BETA2, CDF, OMEGAF)
SUBROUTINE WICRSL

(1) Description:

The subroutine WICRSL is used for the calculation of loss due to the rough surface when large droplets are presented either by themselves or along with small droplets.

Using the experimental results on pipes roughened with sand, L. Prandtl and H. Schlichting carried out a correlation to obtain the friction coefficient on a rough place (Ref. 26). The correlation was based on the logarithmic velocity distribution law for rough pipes in the form, namely

\[ \frac{U}{v^*} = 2.5 \ln \left(\frac{Y}{k}\right) + B \]

where \( v^* \) is friction velocity; \( k \) is roughness of surface, and \( B \) is a roughness function which depends on the roughness parameter, \( v^*k/r \).

In the completely rough regime, they obtained the following relation for the drag coefficient for a plate.

\[ c_{Dr} = (1.81 + 1.62 \log_{10} \frac{x}{k})^{-2.5} \]

In the present case, \( x \) is replaced by the chord length, \( c \), and the surface roughness \( k \) is assumed to be the same as the order of mean diameter of large droplets.

Thus, the total pressure loss coefficient due to turbulent friction over a rough film surface on a rotor becomes the following.

\[ \omega_r = c_{Dr} \left( \frac{c}{S} \right) \frac{\cos^2 \beta_1}{\cos^3 \beta_m} \]
Input Variables:

- SIGUMA: solidity
- BETA1: blade inlet flow angle
- BETA2: blade outlet flow angle
- CHORD: chord length
- DL: droplet diameter

Output Variables:

- CDR: drag coefficient
- OMEGAR: total pressure loss coefficient

Usage:

CALL WICRSL (SIGUMA, BETA1, BETA2, CHORD, DL, CDR, OMEGAR)

SUBROUTINE WICVT

Description:

The subroutine WICVT is used for the calculation of velocity triangle components and angles. Typical velocity diagram for a compressor stage is presented in Fig. A.2.1.

Input Variables:

- ISTAGE: stage at which performance calculation is carried out
- ASPEED: acoustic speed
ALFA1  absolute flow angle at rotor inlet
VZ    axial velocity
AK1   constant in Eq. (A.3.6)'
AK3   constant in Eq. (A.3.1)' and (A.3.2)'

(3) Output Variables:

V1    absolute velocity at rotor inlet
VS1   tangential component of V1
WS1   tangential component of W1
BETA1 relative flow angle at rotor inlet
W1    relative velocity at rotor inlet
BETA2 relative flow angle at rotor outlet
WS2   tangential component of W2
VS2   tangential component of V2
ALFA2 absolute flow angle at rotor outlet
W2    relative velocity at rotor outlet
VZ    absolute velocity at rotor outlet
ALFA3 absolute flow angle at stator outlet
V3    absolute velocity at stator outlet

(4) Usage:

CALL WICVT (ISTAGE, ASPEED, ALFA1, VZ, V1, VS1, WS1,
            BETA1, W1, BETA2, WS2, VS2, ALFA2, W2, V2,
            ALFA3, V3, AK1, AK3)
SUBROUTINE WICCEN

(1) Description:

The subroutine WICCEN is used for the calculation of spanwise replacement of droplets due to centrifugal action.

Three forces act on a droplet moving through a fluid: (1) the external force consisting of gravitational and and centrifugal forces; (2) the buoyancy force, which acts parallel to the external force, but in the opposite direction; and (3) the drag force, which appears whenever there is relative motion between the droplet and the fluid, and acts parallel to the direction of motion but in the opposite direction. In the present case, the direction of motion of a droplet relative to the fluid is not parallel to the direction of the external and buoyant forces, and therefore the drag force makes an angle with the other two forces. However, under the one-dimensional approximation, the lines of action of all forces acting on the droplet are co-linear and therefore the forces may be added in obtaining a balance of momentum, as follows:

\[ \frac{m}{g_c} \frac{du}{dt} = F_e - F_b - F_D \]

where \( F_e, F_b \) and \( F_D \) are the external, buoyancy and drag forces respectively.

The external force can be expressed as the product of mass and acceleration, \( a_e \), of the droplet due to this force, and therefore

\[ F_e = \frac{m}{g_c} a_e \]
In the present case, because of the large rotor speeds, the centrifugal acceleration is far larger than the gravitational acceleration. Thus

\[ a_e = r\omega^2 \]

where \( r \) is the radius and \( \omega \), the angular velocity. The acceleration can also be written as follows:

\[ a_e = V_\theta^2/r \]

where \( V_\theta \) is the circumferential velocity of the droplet. For droplets passing through a rotor blade passage, the circumferential component of the relative velocity, \( W_\theta \), should be used in place of \( V_\theta \). When there is a large change in whirl velocity between the inlet and outlet of a blade row, a mean value of velocity may be more applicable.

The buoyancy force is, by Archimedes' Principle, the product of the mass of the fluid displaced by the droplet and the acceleration from the external force. The mass of fluid displaced is \((m/\rho_w)\rho_g\), where \( \rho_w \) is the density of water and \( \rho_g \) is the density of the surrounding fluid. The buoyancy force is then given

\[ F_b = m\rho_g a_e / \rho_w g_c \]

The drag force is expressed by the relation,

\[ F_d = C_D \frac{\rho_\text{air} v^2}{2} A_p \]

where \( C_D \) is the drag coefficient and \( A_p \) is the projected area of the droplet measured in a plane perpendicular to the direction of motion of the droplet. The drag coefficient
$C_D$ can be expressed in a general form as follows:

$$C_D = \frac{b_1}{Re^n}$$

where $Re$ is the Reynolds number based on relative velocity between gas and droplet. The constants $b_1$ and $n$ are as follows.

- $b_1 = 24.0$, $n = 1.0$ when $Re < 1.9$
- $b_1 = 18.5$, $n = 0.6$ when $1.9 < Re < 500$
- $b_1 = 0.44$, $n = 0.0$ when $500 < Re < 200,000$.

The equation of droplet motion then becomes the following:

$$\frac{du}{dt} = \frac{A}{r} - B u^{2-n}$$

where

$$A = (W_0)^2 \cdot (1-\rho_g/\rho_w)$$
$$B = 3 u^n b_1 \rho_g^{1-n}/4 \rho_w D^{1+n},$$

and $D$ being the average droplet diameter. Over a small time interval, the equation of motion can be written as follows:

$$\Delta u = (A/r - B \cdot u^{2-n}) \Delta t$$

This equation can be used to determine the radial location of a droplet in a stage as follows:

(i) Select the initial values for $u_1$ and $r_1$.
(ii) Calculate the Reynolds number to determine the values of $b_1$ and $n$.
(iii) Calculate $A$ and $B$. 

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(iv) Calculate the change of $u$ during time interval $\Delta t$.

(v) Calculate the new velocity $u_2$.

\[ u_2 = u_1 + \Delta u \]

(vi) Calculate the change in location of droplet in terms of $\Delta r$.

\[ \Delta r = (u_1 + u_2) / 2.0 \cdot \Delta t \]

(vii) Calculate the new radial location.

\[ r_2 = r_1 + \Delta r \]

(viii) Repeat the calculation for new value of $u_2$ and $r_2$ and progressively extend the calculation.

The time interval should be sufficiently small in order to obtain reasonable accuracy. As stated in Section 2.1.3 in Chapter II of this Report, the length between the leading and trailing edges of a blade is divided into ten steps. The time interval $\Delta t$ is then given by the relation, namely

\[ \Delta t = \frac{\text{chord}}{V} \times \frac{1}{10} \]

where $V$ is the velocity of moisture in the blade passage.

(2) Input Variables:

- RZERO: droplet spanwise location at rotor inlet
- UZERO: droplet spanwise velocity at rotor inlet
- DD: droplet diameter
- VZ: axial velocity
- DELZZ: axial length of a stage
- ALFAAV: average flow angle
- FN: rotor blade rotational speed
IRS        index for rotor or stator
RHOGAS     density
RHUB       radius at hub
XG         mass fraction of gas phase
XA         mass fraction of dry air
XVV        mass fraction of vapor
XCH4       mass fraction of methane
RTIPIN     radius at blade tip

(3) Output Variables:
R2         droplet spanwise location blade outlet
U2         droplet spanwise velocity at blade outlet
ITIP       index for droplet spanwise location
VZTIME     time in which flow pass through a stage

(4) Usage:
CALL WICCEN (RZERO, VZERO, DD, VZ, DELZZ, ALFAAV, FN, IRS,
             RHOGAS, RHUB, R2, U2, ITIP, VZTIME, XG, XA,
             XVV, XCH4, RTIPIN)

SUBROUTINE WICDMS

(1) Description:
The subroutine WICDMS is used for the calculation of amount
of small droplets which is centrifuged.

(2) Input Variables:
IPRINT       index for printout
IRAD         index for spanwise location
AMASW1  mass flow rate of water at rotor inlet
AMASWT  mass flow rate of droplet
AMASW   mass flow rate of droplet
R1      droplet spanwise location rotor inlet
R2      droplet spanwise location at rotor outlet
STAREA  streamtube area
RSTAVE  radius of streamtube at its center
RTIP    radius at blade tip

(3) Output Variables:
DMIN    amount of water that is centrifuged and enters into a streamtube
DMOUT   amount of water that is centrifuged and leaves from a streamtube
AMASW2  mass fraction of water at rotor outlet after correction for centrifugal action
DELMAS  net amount of water that is centrifuged

(4) Usage:
CALL WICOMS (IPRINT, IRAD, AMASW1, AMASWT, AMASW, R1,
             R2, STAREA, RSTAVE, RTIP, DMIN, DMOUT,
             AMASW2, DELMAS)

SUBROUTINE WICDML

(1) Description:
The subroutine WICDML is used for the calculation of amount of large droplets which is centrifuged.
Input Variables:

- IPRINT: index for printout
- IRAD: index for spanwise location
- AMASW1: mass flow rate of water at rotor inlet
- AMASWT: mass flow rate of droplet
- AMASW: mass flow rate of droplet
- R1: droplet spanwise location rotor inlet
- R2: droplet spanwise location at rotor outlet
- STAREA: streamtube area
- RSTAVE: radius of streamtube at its center
- RTIP: radius at blade tip

Output Variables:

- DMIN: amount of water that is centrifuged and enters into a streamtube
- DMOUT: amount of water that is centrifuged and left from a streamtube
- AMASW2: mass fraction of water at rotor outlet after correction for centrifugal action.
- DELMAS: net amount of water that is centrifuged

CALL WICDML (IPRINT, IRAD, AMASW1, AMASWT, AMASW, R1, R2, STAREA, RSTAVE, RTIP, DMIN, DMOUT, AMASW2, DELMAS)

SUBROUTINE WICDRG

Description:

The subroutine WICDRG is used for the calculation of drag.
force on droplet.

(2) Input Variables:

D  droplet nominal diameter
DELV1  relative velocity between droplet and gas phase at blade inlet
RHGAS1  density of gas phase at blade inlet
RHGAS2  density of gas phase at blade outlet

(3) Output Variables:

CD2  drag coefficient
DELV2  relative velocity between droplet and gas phase at blade outlet
DRAGI  drag force
RE  Reynolds number

(4) Usage:

CALL WICDRG (D, DELV1, RHGAS1, RHGAS2, CD2, DELV2, DRAG1, RE)

SUBROUTINE WICMAC

(1) Description:

Subroutine WICMAC calculates the Mach number in the gas-water droplet mixture. First the acoustic speed in gaseous phase is determined by iteration as follows:
(i) Assume Mach number and calculate static temperature and density.

\[ p = \left(1 + \frac{i - 1}{2} M^2 \right)^{-1} P_0 \left(1 + \frac{i - 1}{2} M^2 \right)^{-1/(i-1)} P_0 / R T_0 \]

(ii) Calculate acoustic speed in gaseous phase

\[ a_g = (\gamma R T g_c)^{0.5} \]

(iii) Calculate the axial velocity

\[ V_z = \dot{m} / \rho A \]

(iv) Calculate absolute velocity

\[ V_1 = V_3 / \cos \alpha_1 \]

(v) Calculate Mach number

\[ M_1 = V_1 / a_g \]

Compare the calculated Mach number with the assumed value in (i). Iterate steps (i) to (v) until the desired accuracy is obtained. After determining the acoustic speed in gaseous phase, function WICASD is called to determine the acoustic speed in droplet-laden gas flow.

(2) Input Variables:

ISTAGE stage number

AMASSM mixture mass flow rate
TOIG  total temperature of gaseous phase
PRES  total pressure
XW1   total water content
ALFA  stator outlet angle of the previous stage
RMIX  gas content of gaseous phase
CPMIX specific heat at constant pressure for gaseous phase

(3) Output Variables:
M     Mach number
VZ    axial velocity
C     acoustic speed in mixture

(4) Usage:

CALL WICMAC (ISTAGE, AMASSM, TOIG, PRES, M, VZ, C, XW1, ALFA, RMIX, CPMIX)

FUNCTION WICASD

(1) Description:

Function WICASD calculates the acoustic speed in droplet-laden gas flow. The following equation is used (Ref.27).

\[
a = \left( \frac{(1-\sigma_v)\rho_g + \sigma_v\rho_w}{\rho_g a_g + \frac{\sigma_v}{\rho_w a_w}} \right)^{-\frac{k}{2}}
\]

where

\[a_g = \text{acoustic speed in gaseous phase}\]
\[ a_w = \text{acoustic speed in water} \]

\[ \rho_g = \text{density of gaseous phase} \]

\[ \rho_w = \text{density of water} \]

\[ \sigma_v = \text{particulate liquid volume fraction} \]

\[ x_w = \text{particulate liquid mass fraction} \]

\[ \sigma_v = x_w \rho_g / \left( \rho_w - x_w (\rho_w - \rho_g) \right) \]

(2) Input Variables:

\[ X_W \quad \text{total water content} \]

\[ \text{RHOG} \quad \text{density of gas phase} \]

\[ \text{CG} \quad \text{acoustic speed of gaseous phase} \]

(3) Output Variable:

\[ \text{WICASD} \quad \text{acoustic speed in gas-water droplet mixture} \]

(4) Usage:

\[ \text{WICASD} \ (XW, \ \text{RHOG}, \ \text{CG}) \]

**SUBROUTINE WICBOA**

(1) Description:

Subroutine WICBOA calculates the blade outlet flow angle based on Swan's correlation curves (Ref. 24). Swan's curves and the concept of equivalent diffusion ratio are also described in Subroutine WICGSL.
(2) Input Variables:

OMEGAS  total pressure loss coefficient at design point
SIGUMA  solidity
BETIS  blade inlet angle at design point
BET2S  blade outlet angle at design point
AINCIS  incidence at design point
ADEVIS  deviation at design point
AMACHI  blade inlet Mach number
BETI  blade inlet flow angle

(3) Output Variables:

DEQS  equivalent diffusion ratio at design point
DEQN  equivalent diffusion ratio
SITACS  ratio of wake momentum thickness to chord at design point
SITACN  ratio of wake momentum thickness to chord design point
BET2N  blade outlet angle

(4) Usage:

CALL WICBOA (OMEGAS, SIGUMA, BETIS, BET2S, AINCIS, ADEVIS,
AMACHI, BETI, DEQS, DEQN, SITACS, SITACN, BET2N)

SUBROUTINE WICEDD

(1) Description:

Subroutine WICEDD is called in Subroutine WICBOA and WICGSL. The equivalent diffusion ratio at design point, $D_{eq}$, and the ratio of wake momentum thickness to chord at design point, $(\frac{\delta}{c})^*$, are obtained from the following equations:
\[
D_{eq} = \frac{\cos \beta_2}{\cos \beta_1} \frac{V_{z1}}{V_{z2}} \left(1.12 + 0.61 \frac{\cos^2 \beta_1}{\sigma} K\right) \cdot AK3
\]

\[
\left(\frac{\theta}{c}\right) = \frac{\bar{\omega}^* \cos \beta^*}{2 \sigma} \left(\frac{\cos \beta^*}{\cos \beta^*}\right)^2
\]

where

\[
K = \tan \beta^* - \frac{r_1}{r_1} \frac{V_{z2}}{V_{z1}} \tan \beta^* - \frac{\omega r_1}{V_{z1}} \left(1 - \frac{r_2}{r_1^2}\right)
\]

(2) Input Variables:
- AK3: constant, normally one
- VZ1: axial velocity at blade inlet
- VZ2: axial velocity at blade outlet
- UR1: rotor blade speed at rotor inlet
- R1: radius at blade inlet
- R2: radius at blade outlet
- BET1S: blade inlet flow angle at design point
- BET2S: blade outlet flow angle at design point
- SIGUMA: solidity
- OMEGAS: total pressure loss coefficient at design point

(3) Output Variables:
- DEQS: equivalent diffusion ratio at design point
- SITACCS: ratio of wake momentum thickness to chord at design point

(4) Usage:
CALL WICEDD (AK3, VZ1, VZ2, UR1, R1, R2, BET1S, BET2S, SIGUMA, OMEGAS, DEQS, SITACCS)
FUNCTION WICED

(1) Description:

Function WICED is called in Subroutines WICBOA and WICGSL. The equivalent diffusion ratio is obtained from the following equation.

\[ D_{eq} = \frac{\cos \beta_2}{\cos \beta_1} \frac{V_{Z1}}{V_{Z2}} \left( 1.12 + k (i-i^*)^{1.43} + 0.61 \frac{\cos \beta_1}{\omega} K \right) \cdot AK3 \]

where

\[ K = \frac{\tan \beta_1 - \frac{r_2 V_{Z2}}{r_1 V_{Z1}} \tan \beta_1 - \frac{\omega r_1}{V_{Z1}} (1 - \frac{r_2^2}{r_1^2})}{\frac{\omega r_1}{V_{Z1}} (1 - \frac{r_2^2}{r_1^2})} \]

and where \( k = 0.0117 \) for NACA 65 \((A_{10})\) blades and \( k = 0.007 \) for the C4 airfoils.

(2) Input Variables:
- AK3 constant, normally one
- VZ1 axial velocity at blade inlet
- VZ2 axial velocity at blade outlet
- URI rotor blade speed at rotr inlet
- R1 radius at blade inlet
- R2 radius at blade outlet
- BET1 blade inlet flow angle
- BET2 blade outlet flow angle
- SIGUMA solidity
- AINCIS incidence at design point
- AINCI incidence

(3) Output Variable:
- WICED equivalent diffusion ratio
FUNCTION WICMTK

(1) Description:

Function WICMTK is called in Subroutines WICBOA and WICGSL. The ratio of wake momentum thickness and chord are obtained from the following equations.

\[
\frac{\theta}{c} = \left( \frac{\theta}{c} \right)^* + (0.827 M_1 + 2.675 M) (D_{eq} - D_{eq}^*)^2 \cdot AK2 \\
\text{for } D_{eq} > D_{eq}^*
\]

\[
\frac{\theta}{c} = \left( \frac{\theta}{c} \right)^* + (2.80 M_1 - 8.71 M_1^2 + 9.36 M_1^3) (D_{eq} - D_{eq}^*)^2 \cdot AK2 \\
\text{for } D_{eq} < D_{eq}^*
\]

(2) Input Variables:

AK2 constant, normally one
SITACS ratio of wake momentum thickness to chord at design point
AMACH1 blade inlet Mach number
DELDEQ difference between equivalent diffusion ratio and equivalent diffusion ratio at design point.

(3) Output Variables:

WICMTK ratio of wake momentum thickness to chord

(4) Usage:

WICMTK (AK2, SITACS, AMACH1, DELDEQ, AK2)
FUNCTION WICLOS

(1) Description;

Function WICLOS is called in Subroutine WICGSL and calculates the total pressure loss coefficient from the following equation:

\[ \bar{\omega} = \left( \frac{\alpha}{c} \right) \frac{2\sigma}{\cos \beta_2} \left( \frac{\cos \beta_1}{\cos \beta_2} \right)^2 \]

(2) Input Variables:
BET1  blade inlet flow angle
BET2  blade outlet flow angle
SIGUMA solidity
SITA  ratio of momentum thickness to chord

(3) Output Variable:
WICLOS  total pressure loss coefficient

(4) Usage:

WICLOS (BET1, BET2, SIGUMA, SITA)

SUBROUTINE WICIRS

(1) Description:

Subroutine WICIRS is called at outlet of rotor and performs the calculation of droplet impingement and rebound in rotor passage for small droplet.

(2) Input Variables:
ISTAGE  stage number
RTIPIN  blade tip radius
XW1  mass fraction of small droplet
XG  mass fraction of gaseous phase 
RHOG1  density of gaseous phase 
BETA1  rotor inlet relative flow angle 
W1  rotor inlet relative velocity 

(3) Output Variables: 

WW1 amount of water that impacts stagnation region of blade 
WW2 amount of water that impact aft of blade 
WW total amount of water that impact blade 

(4) Usage: 

CALL WICIRS (ISTAGE, RTIPIN, XW1, XG, RHOG1, BETA1, W1, WW1, WW2, WW) 

SUBROUTINE WICIRL 

(1) Description: 

Subroutine WICIRL is called at outlet of rotor and performs the calculation of droplet impingement and rebound in rotor passage for large droplet. 

(2) Input Variables: 

ISTAGE  stage number 
RTIPIN  blade tip radius 
XW1  mass fraction of large droplet 
XG  mass fraction of gaseous phase 
PHOG1  density of gaseous phase 
BETA1  rotor inlet relative flow angle 
W1  rotor inlet relative velocity 

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Output Variables:

- WW1: amount of water that impacts upper surface of blade
- WW2: amount of water that impacts lower surface of blade
- WW: total amount of water that impacts blade surface

Usage:

CALL WICIRL (ISTAGE, RTIPIN, XW, XG, RHOGI, BETAI, Wi, WW1, WW2, WW)

SUBROUTINE WICISS

Description:

Subroutine WICISS is called outlet of stator and performs the calculation of droplet impingement and rebound in stator passage for small droplet.

Input Variables:

- ISTAGE: stage number
- RTIPIN: blade tip radius
- XW: mass fraction of small droplet
- XG: mass fraction of gaseous phase
- RHOGI: density of gaseous phase
- ALFA2: stator inlet absolute flow angle
- Wi: stator inlet absolute velocity
Output Variables:

WW1  amount of water that impact stagnation region of blade
WW2  amount of water that impact off of blade
WW   total amount of water that impact the blade

Usage:
CALL WICISS (ISTAGE TRIPIN, XW, XG RHOG1, ALFA2, WI, WW1, WW2, WW)

SUBROUTINE WICISL

Description:
Subroutine WICISL is called at outlet of stator and performs the calculation of droplet impingement and rebound in stator passage for large droplet.

Input Variable:

ISTAGE  stage number
RTIPIN  blade tip radius
XW      mass fraction of large droplet
XG      mass fraction of gaseous phase
RHOG1   density of gaseous phase
ALFA2   stator inlet absolute flow angle
WI      stator inlet absolute velocity

Output Variables:

WW1  amount of water that impact upper surface of blade
WW2  amount of water that impact lower surface of blade
total amount of water that impact on blade surface

(4) Usage:
CALL WICISL (ISTAGE, RTIPIN, XW, XG, RHOG1, ALFA2, W1, WW1, WW2, WW)

SUBROUTINE WICWAK

(1) Description:

Subroutine WICWAK is called at rotor outlet and stator outlet, and calculates the droplet size of water that is re-entrained at trailing edge of rotor and stator blades.

The size of droplet which is re-entrained into the wake at the blade trailing edge is calculated as follows:

(i) Assume a value for a droplet diameter, d, that is re-entrained into wake.

(ii) Calculate the stability number, SN.
    \[ SN = \frac{\mu_f}{\rho_0 \sigma d g_c} \]

(iii) Calculate the critical Weber number
    \[ W_e = 12 \left( 1 + (SN)^{0.36} \right) \]

(iv) Calculate the largest stable droplet diameter
    \[ d_{\text{max}} = \frac{W_e}{\rho_g \nu^2} \frac{\sigma g_c}{V^2} \]

(v) Compare the assumed droplet diameter with the calculated one. Iterate entire steps until the satisfactory agreement is obtained.
(2) Input Variables:

- RHOG: density of gaseous phase
- V: velocity of gaseous phase for small droplet or relative velocity between droplet and gaseous phase for large droplet

(3) Output Variables:

- DWAKE: droplet size that re-entrained at trailing edge in (ft³)
- DWAKEM: droplet size that re-entrained at trailing edge in (µm)

(4) Usage:

CALL WICWAK (RHOG, V, DWAKE, DWAKEM)

SUBROUTINE WICHET

(1) Description:

Subroutine WICHET is called at end of stage to perform the heat transfer calculation between water droplet and gaseous phase. The heat transfer rate can be determined from the following equation

\[
\frac{dh}{dt} = h_h A (T_g - T_w)
\]

where \( h_h \) is the heat transfer coefficient, \( A \), the droplet surface area, \( T_w \), the droplet surface temperature, and \( T_g \), the temperature of the surrounding gas. The heat transfer coefficient can be expressed as follows:

\[
h_h = \frac{k_a}{D_d} \cdot Nu
\]
where $k_a$ is the thermal conductivity of air, and $Nu$, the Nusselt Number. The Nusselt number can be expressed in terms of the dimensionless groups as follows:

$$Nu = 2.0 + 0.6 \cdot (Re)^{0.50} \cdot (Pr)^{0.33}$$

where $Re$ is the Reynolds number based on the relative velocity between the droplet and the surrounding air, and $Pr$ is Prandtl number.

After calculating the temperature rise of the water and gas phase due to the work done by the rotor, the heat transfer calculation is carried out as follows:

(i) Calculate the average droplet diameter, $D_d$.

(ii) Calculate the number of droplets, $N_d$.

$$N_d = \frac{\dot{m}_w}{\rho_w \cdot \frac{4}{3} \pi (D_d/2)^3} \cdot \frac{\Delta z}{V_z}$$

where $\dot{m}_w$ is the mass flow rate of water phase, $\rho_w$, the density of water, $V_z$, the axial direction velocity, and $\Delta z$, the axial length of one stage.

(iii) Calculate the droplet surface area, $A$.

(iv) Calculate the Nusselt number, $Nu$.

(v) Calculate the heat transfer coefficient, $h_h$.

(vi) Calculate the stage outlet temperature for droplet and gas without heat transfer, that is:

$$T_{g_2} = T_{g_1} + (\Delta T_g)_{wk}$$

$$T_{w_2} = T_{w_1} + (\Delta T_w)_{wk}$$

where $(\Delta T_g)_{wk}$ and $(\Delta T_w)_{wk}$ are the temperature rise of gas and water due to work done by rotor.
(vii) Calculate the amount of heat transferred from the gas to the droplet.

\[ \Delta H = h_h A (T_{g2} - T_{w2}) \]

(viii) Calculate the temperatures rise of the droplet and the temperature drop of the surrounding gas.

\[ (\Delta H_g)_{ht} = \Delta H/m_g C_s \]
\[ (\Delta H_w)_{ht} = \Delta H/m_w C_w \]

where \( C_w \) is the specific heat for water and \( C_s \) is the humid heat for air-water mixture.

(ix) Calculate the stage outlet temperature for droplet and gas.

\[ T_{g2} = T_{g1} + (\Delta T_g)_{wk} - (\Delta T_g)_{ht} \]
\[ T_{w2} = T_{w1} + (\Delta T_w)_{wk} + (\Delta T_w)_{ht} \]

(X) Using the temperature calculated in step (ix), repeat the steps (vii) to (ix) until a desired accuracy is obtained.

(2) Input Variables:

- \( T_{G1} \): temperature of gaseous phase at stage inlet
- \( T_{G3} \): temperature of gaseous phase at stage outlet
- \( T_{W1} \): temperature of droplet at stage inlet
- \( T_{W3} \): temperature of droplet at stage outlet
- \( DAVEN2 \): droplet nominal diameter at stage inlet
- \( DEVEN \): droplet nominal diameter at stage outlet
- \( DELZI \): length of stage
- \( VZ \): axial velocity
- \( WMASS1 \): mass flow rate of water
- \( VMASS1 \): mass flow rate of water vapor
AMASS  mass flow rate of dry air
CHMASS mass flow rate of methane
DPG  specific heat constant pressure to gaseous phase
CPW specific heat of water
RE  Reynolds number based on relative velocity between droplet and gaseous phase.

(3) Output Variables:
DELIGH temperature drop in gaseous phase due to heat transfer between water droplet and gaseous phase
DELTWH temperature rise in droplet due to heat transfer between water droplet and gaseous phase

(4) Usage:
CALL WICHET (TG1, TG3, TW3, DAVEN2, DAVEN, DELZI, VZ, WMASS1, VMASS1, AMASS, CHMASS, CPG, CPW, DELIGH, DELTWH, RE)

SUBROUTINE WICMAS

(1) Description:

Subroutine WICMAS is called at end of stage to perform the mass transfer calculation between water droplet and gas phases.

The mass transfer rate can be calculated by the following equation

$$\frac{dm}{dt} = h_mA (C_{wb} - C_w)$$
where \( h_m \) is the mass transfer coefficient, \( A \), the droplet surface area, \( C_{wb} \), the water vapor concentration at droplet surface, and \( C_w \), the water vapor concentration in fluid flow around droplet.

Since the density represents the mass concentration, and the vapor is almost a perfect gas, the mass transfer rate can be expressed in terms of vapor pressure as follows:

\[
\frac{dm}{dt} = h_m A (p_{wb} - p_w)
\]

or

\[
\frac{dm}{dt} = h_m A \left( \frac{p_{wb}}{T_{wb}} - \frac{p_w}{T_w} \right) \cdot \frac{1}{R_v}
\]

where \( R_v \) is the gas constant for water vapor, \( p_{wb} \), the vapor pressure at droplet surface, \( p_w \), the vapor pressure in fluid flowing around droplet, \( T_{wb} \), the vapor temperature at droplet surface, and \( T_w \), the vapor temperature in fluid flowing around droplet.

The surface area, \( A \), for the droplet cloud is given by the relation,

\[ A = \pi D_d^2 N_d \]

where \( D_d \) is the average droplet diameter, and \( N_d \), the number of droplets.

The mass transfer coefficient, \( h_m \), is expressed as follows:

\[ h_m = \frac{D_v}{D_d} \cdot Sh \]

A semi-empirical equation for the diffusion coefficient in gases is given by the following: (Reference 28)

\[ D_v = 435.7 \frac{T^{3/2}}{p\left(\frac{1}{n_A} + \frac{1}{n_B}\right)^{1/2}} \]

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where $D_v$ is in square centimeters per second, $T$ is in degree Kelvin, $p$ is the total system pressure in newtons per square meter, and $V_A$ and $V_B$ are the molecular volumes of constituents A and B as calculated from the atomic volumes. $M_A$ and $M_B$ are the molecular weights of constituents A and B. For water-air systems, the numerical values of $V_A$, $V_B$, $M_A$ and $M_B$ are given as follows:

$$V_A = V_{\text{air}} = 29.9 \quad M_A = M_{\text{air}} = 28.9$$

$$V_B = M_{\text{water}} = 18.8 \quad M_B = M_{\text{water}} = 18.0$$

When the relative velocity between a single droplet and the surrounding fluid approaches zero, the following relationship is used to determine the mass transfer rate: $Sh = 2.0$.

Mass transfer rates increase with increase in relative velocity between the droplet and the surrounding air due to the additional mass transfer caused by the convection in the boundary layer around the droplet. The mass transfer coefficient from a spherical droplet can be expressed in terms of dimensionless groups as follows:

$$Sh = 2.0 + k \left( \frac{Re}{Re_{\text{crit}}} \right)^X \left( \frac{Sc}{Sc_{\text{crit}}} \right)^Y$$

where $Re$ is the Reynolds number based on relative velocity, which expresses the ratio of inertial force to viscous force, and $Sc$ is the Schmidt number, which expresses the ratio of kinetic viscosity to molecular diffusivity.

There is much discussion over the values of $x$, $y$, and $k$. The form most widely applied is the Ranz and Marshall equation which is

$$Sh = 2.0 + 0.6 \left( \frac{Re}{Re_{\text{crit}}} \right)^{0.50} \left( \frac{Sc}{Sc_{\text{crit}}} \right)^{0.33}$$
The procedure for determining the mass transfer rate is as follows.

(i) Calculate the Sherwood number, $Sh$.

(ii) Calculate the diffusion coefficient, $D_v$.

(iii) Calculate the average droplet size, $D_d$.

(iv) Calculate the mass transfer coefficient, $h_m$.

(v) Calculate the total number of droplets, $N_d$.

(vi) Calculate the total surface area for all droplets.

(vii) Calculate the water vapor pressure at droplet surface, $P_{wb'}$, based on the droplet surface temperature, $T_s$.

(viii) Assume the vapor pressure, $p_w$, and set $p_w = (p_w)_a$.

(ix) Calculate the mass transfer rate, $\frac{dm}{dt}$.

(x) Calculate the the new value of water mass flow rate.

\[
th{\text{w}} = \hat{m}_w - \frac{dm}{dt}
\]

(xi) Calculate the new value of vapor mass flow rate.

\[
th{\text{v}} = \hat{m}_v + \frac{dm}{dt}
\]

(xii) Calculate the specific humidity, $W$.

\[
W = \frac{\hat{m}_v}{\hat{m}_a}
\]

where $m_a$ is the air mass flow rate.

(xiii) Calculate the vapor pressure.

(xiv) Compare the calculated value, $(p_w)_c$, with the assumed value $(p_w)_a$.

If $(p_w)_c$ agrees reasonably well with the assumed value $(p_w)_c$ proceed to step (xv). Otherwise, steps (viii) to (xiv) should be repeated.

(xv) Using the determined $p_w$, the mass transfer rate is calculated.

Also, the specific humidity can be determined by the following equation:

\[
W = 0.6219 \frac{p_w}{p - p_w}
\]
(2) Input Variables:

- HW1: specific humidity at stage inlet
- TW1: temperature of droplet at stage inlet
- TW2: temperature of droplet at stage outlet
- PP1: pressure of gaseous phase stage inlet
- PP2: pressure of gaseous phase at stage outlet
- TG1: temperature of gaseous phase at stage inlet
- TG2: temperature of gaseous phase at stage outlet
- DZ: length of stage
- VZ: axial velocity
- DDAVE1: droplet nominal diameter at stage inlet
- DDAVE2: droplet nominal diameter at stage outlet
- AMASS: mass flow rate of air
- RE: Reynolds number based on relative velocity between droplet and gaseous phase
- VMASS1: mass flow rate of water vapor at stage inlet
- WMASS1: mass flow rate of water droplet at stage outlet

(3) Output Variables:

- HW2: specific humidity at stage outlet
- VMASS2: mass flow rate of water vapor at stage outlet
- WMASS2: mass flow rate of water droplet at stage outlet
- DMDTAV: average mass transfer rate across stage

(4) Usage:

CALL WICMAS (HW1, TW1, TW2, PP1, PP2, TG1, TG2, DZ, PWb1, PWb2, PW1, PW2, VZ, DDAVE1, DDAVE2, HW2, VMASS1, VMASS2, WMASS1, WMASS2, DMDTAV, AMASS, RE)
FUNCTION WICMTR

(1) Description:

Function WICMTR is called in Subroutine WICMTR and calculates the mass transfer rate.

(2) Input Variables:

TTG  temperature of gaseous phase
TTW  temperature of water droplet
PPP  pressure of gaseous phase
DAVW droplet nominal diameter
VZ   axial velocity
DZ   length of stage
MMASS mass flow rate of mixture
PW   vapor pressure
RE   Reynolds number based on relative velocity between droplet and gaseous phase

(3) Output Variable:

DMDT mass transfer rate

(4) Usage:

WICMTR (TTG, TTW, PPP, DAVW, VZ, DZ, MMASS, PW, RE)

FUNCTION WICPWB

(1) Description:

Function WICPWB calculates the saturation pressure for water vapor as a function at temperature as follows:

\[ \log_{10} p_s = A - \frac{B}{T} \]
where units are (Kg/cm²) for $p_s$ and (K) for $T$. The values of constant $A$ and $B$ are given as follows:

$$A = 5.97780, \quad B = 2224.4 \quad \text{when } 20^\circ C < T < 100^\circ C$$
$$A = 5.64850, \quad B = 2101.1 \quad \text{when } 100^\circ C < T < 200 \, C$$
$$A = 5.45142, \quad B = 2010.8 \quad \text{when } 200 \, C < T < 350 \, C$$

(2) Input Variable:
TWB \quad \text{temperature of gaseous phase}

(3) Output Variable:
WICPWB \quad \text{saturation pressure for water vapor}

(4) Usage:
WICPWB (TWB)

**FUNCTION WICNEW**

(1) Description:

Function WICNEW is used to estimate the new trial value in the iteration procedure. Figure A.3.2 shows how to determine the new trial value.

(2) Input Variables:
X1 \quad \text{first trial value}
Y1 \quad \text{calculated value corresponds to X1}
X2 \quad \text{second trial value}
Y2 \quad \text{calculated value corresponds to X2}

(3) Output Variable:
WICNEW \quad \text{new trial value}

(4) Usage:
WICNEW (X1, Y1, X2, Y2)
**FUNCTION WICTAN**

(1) Description:

Function WICTAN(X) is used to obtain the ratio of SINE(X) to COSINE(X), that is, TAN(X).

(2) Input Variable:

X angle

(3) Output Variable:

WICTAN value of TAN(X)

(4) Usage:

WICTAN(X)

**FUNCTION WICBPT**

(1) Description:

Function WICBPT calculates the temperature at boiling point.

(2) Input Variables:

TSTAG temperature
PSTAGE pressure

(3) Output Variable:

WICBPT temperature at boiling point

(4) Usage:

WICBPT (TSTAG, PSTAGE)
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FUNCTION WICSH

(1) Description

Function WICSH calculates the specific humidity.

(2) Input Variables:
TSTAGE temperature
PSTAG pressure

(3) Output Variable:
WICSH specific humidity

(4) Usage:
WICSH (TSTAG, PSTAG)

SUBROUTINE WICSIZ

(1) Description:

Subroutine WICSIZ is called at outlet of rotor and stator to determine the nominal droplet sizes. It is assumed that two kinds of droplets exist at inlet of compressor; namely, small droplet and large droplet. However, at trailing edge of each blade, the new droplets are re-entrained into blade wake. The droplets which are larger than DLIMIT are treated as large droplets and droplets which are smaller than DLIMIT are treated as small droplets. Each droplet size weighted based on its mass fraction in determining the nominal droplet size. Therefore, at outlet of each blade row, Subroutine WICSIZ gives two nominal diameters; one for small droplet and one for large droplet. It may be noted that only two classes of droplets are recognized in the model.
(2) Input Variables:

- **WMASSL**: mass flow rate of large droplet
- **WMASSS**: mass flow rate of small droplet
- **AMING1**: amount of water which is to be re-entrained into wake, originally small droplet
- **AMING2**: amount of water which is to be re-entrained into wake, originally large droplet and upper part
- **AMING3**: amount of water which is to be re-entrained into wake, originally large droplet and lower part
- **DL**: droplet nominal size for large droplet before impingement
- **DS**: droplet nominal size for small droplet before impingement
- **D1**: droplet size associated with AMING1
- **D2**: droplet size associated with AMING2
- **D3**: droplet size associated with AMING3
- **DLIMIT**: largest droplet diameter which can be treated as small droplet

(3) Output Variables:

- **AMSL**: mass flow rate of small droplet after re-entrainment
- **AMLGE**: mass flow rate of large droplet after re-entrainment
- **DSLL**: droplet nominal size for small droplet
- **DLGE**: droplet nominal size for large droplet

(4) Usage:

```fortran
CALL WICSIZ (WMASSL, WMASSS, AMING1, AMING2, AMING3, DL, DS, D1, D2, D3, DLIMIT, AMSLL, AMLGE, DSLL, DLGE)
```

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SUBROUTINE WICPRP

(1) Description:

Subroutine WICPRP determines the flow properties such as gas constant specific, heat ratio, and specific heat at constant pressure for the gaseous mixture. The working equations are as follows:

\[
R_{\text{mix}} = x_a \cdot R_a + x_v \cdot R_v + x_c \cdot R_c
\]

\[
C_{\text{pmix}} = x_a \cdot C_{pa} + x_v \cdot C_{pv} + x_c \cdot C_{pc}
\]

\[
\gamma_{\text{mix}} = (1.0 - \frac{R_{\text{mix}}}{C_{\text{pmix}}})^{-1}
\]

where

\[
x_a = \text{mass fraction of air in gaseous mixture}
\]

\[
x_v = \text{mass fraction of water vapor in gaseous mixture}
\]

\[
x_c = \text{mass fraction of methane in gaseous mixture}
\]

\[
x_a + x_v + x_c = 1
\]

\[
R_a = \text{gas constant of air}
\]

\[
R_v = \text{gas constant of water vapor}
\]

\[
R_c = \text{gas constant of methane}
\]

\[
R_{\text{mix}} = \text{gas constant of mixture}
\]

\[
C_{pa} = \text{specific heat constant pressure for air}
\]

\[
C_{pv} = \text{specific heat constant pressure for water vapor}
\]

\[
C_{pc} = \text{specific heat at constant pressure for methane}
\]
\[ c_{\text{pmix}} = \text{specific heat at constant pressure for mixture} \]

\[ r_{\text{mix}} = \text{specific heat ratio for mixture} \]

(2) Input Variables:

- \( X_{\text{AIR}} \): mass fraction of air in gaseous mixture
- \( X_{\text{H20}} \): mass fraction of water vapor in gaseous mixture
- \( X_{\text{CH4}} \): mass fraction of methane in gaseous mixture
- \( T \): temperature of gaseous mixture

(3) Output Variables:

- \( R_{\text{mix}} \): gas constant of gaseous mixture
- \( c_{\text{pmix}} \): specific heat constant pressure for gaseous mixture
- \( \Gamma \): specific heat ratio of gaseous mixture
- \( G_1 \): value for \( \Gamma / (\Gamma - 1.0) \)
- \( G_2 \): value for \( (\Gamma - 1.0)/2.0 \)
- \( G_3 \): value for \(-1.0 / (\Gamma - 1.0)\)

(4) Usage:

CALL WICPRP (XAIR, XH20, XCH4, T, Rmix, CPMIX, GAMMA, G1, G2, G3)

**FUNCTION WICCPA**

(1) Description

Function WICCPA calculates the specific heat at constant pressure for air as a function of temperature as follows: (Reference 29)

\[ c_p = (a + aT + cT^2 + dT^3 + eT^4)R \]
where units are (J/kg-K) for \( c_p \), (K) for \( T \), and (J/kg-K) for \( R \). The values of coefficients \( a \), \( b \), \( c \), \( d \), and \( e \) are as follows:

\[
\begin{align*}
    a &= 3.65359 \\
    b &= -1.33736 \times 10^{-10} \\
    c &= 3.29421 \times 10^{-6} \\
    d &= -1.91142 \times 10^{-9} \\
    e &= 0.275462 \times 10^{-12}
\end{align*}
\]

(2) Input Variable:
\( T \) temperature

(3) Output Variable:
WICCPh specific heat constant pressure

(4) Usage:
WICCPh \( (T) \)

**FUNCTION WICCPh**

(1) Description:

Function WICCPh calculates the specific heat at constant pressure for water vapor as a function of temperature as follows: (Reference 29)

\[
c_p = (a + bT + cT^2 + dT^3 + eT^4)R
\]

where units are (J/kg-K) for \( c_p \), (K) for \( T \), and (J/kg-K) for \( R \). The values of coefficients \( a \), \( b \), \( c \), \( d \), and \( e \) are as follows:

\[
\begin{align*}
    a &= 4.07013 \\
    b &= -1.10845 \times 10^{-3}
\end{align*}
\]
\[ c = 4.15212 \times 10^{-6} \]
\[ d = -2.96374 \times 10^{-9} \]
\[ e = 0.807021 \times 10^{-12} \]

(2) Input Variable:
\[ T \quad \text{temperature} \]

(3) Output Variable:
\[ \text{WICCPH} \quad \text{specific heat at constant pressure} \]

(4) Usage:
\[ \text{WICCPH} \left( T \right) \]

FUNCTION WICCPIC

(1) Description:
Function WICCPIC calculates the specific heat at constant pressure for methane as a function of temperature as follows: (Reference 29)
\[ c_p = (a + bT + cT^2 + dT^3 + eT^4)R \]
where units are (J/kg-k) for \( c_p \), (K) for \( T \), and (J/kg-K) for \( R \). The values of coefficients \( a, b, c, d, \) and \( e \) are as follows:
\[ a = 3.82619 \]
\[ b = -3.97946 \times 10^{-3} \]
\[ c = 24.5583 \times 10^{-6} \]
\[ d = -22.7329 \times 10^{-9} \]
\[ e = 6.92760 \times 10^{-12} \]

(2) Input Variable:
\[ T \quad \text{temperature} \]

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(3) Output Variable:
WICCPC specific heat constant pressure

(4) Usage:
WICCPC (T)
APPENDIX 4

PROGRAM SOURCE LIST
PROGRAM MAIN(INPUT,OUTPUT,TAPES=INPUT,TAPES=OUTPUT)

C******************************************************************* MAIN 1
C PROGRAM PURDU-WICSTK MAIN 2
C ABSTRACT: MAIN 3
C THIS PROGRAM CODE HAS BEEN PRODUCED FOR THE STUDY OF THE AXIAL FLOW
C COMPRESSOR PERFORMANCE FOR THE GAS-WATER MIXTURE FLOW. MAIN 4
C THE MIXTURE CONSISTES OF TWO TYPES OF DROPLET SIZES AND THREE
C KINDS OF GASEOUS PHASES. THIS PROGRAM CODE IS WRITTEN ESPECIALLY
C FOR AIR+TAPES=INPUT, TAPES=OUTPUT
C FOR AIR+VAPOR+METHANE+SMALL DROPLET+LARGE DROPLET.
C THIS FORTRAN COMPUTER CODE CAN PREDICT THE DESIGN AND OFF-DESIGN
C PERFORMANCE OF AXIAL FLOW COMPRESSOR. STAGE AND OVERAL PERFORMANCE
C ARE OBTAINED BY A STAGE-BY-STAGE CALCULATION.
C THIS COMPUTER PROGRAM CODE HAS BEEN DEVELOPED AT PURDUE UNIVERSITY,
C THERMAL SCIENCE AND PROPULSION CENTER, WEST LAFAYETTE, INDIANA 47906,
C UNDER AIR FORCE CONTRACT F33615-78-C-2401, PRINCIPAL INVESTIGATOR: DR.
C S. M. S. MURTHY, THE AUTHOR OF THIS PROGRAM CODE IS TOSHIAKI TSUCHIYA,
C Graduate Instructor in Research.
C
C****************************************************************************** MAIN 20
C REAL ND, NU, KG, MM, MASS, M MASS
C REAL MMSS
C COMMON TD(7), IUNIT
C COMMON CFL, CF, CPF, CM, CFU, CFA
C COMMON JPERFM, ROH(3), RERUP, RERLOH, RESUP, RESLOH
C COMMON PRED, ROP(8), SRTIP(8), AAAL, AARL, AANA, SAREA(6), SAREAS(7)
C COMMON PG(3), TG(3), XA, XV(3), XCH4, XV(3), XA(3), XH(3), TXH(3)
C COMMON OMEG(7), OMEGR(6), GAFR(6), GAPR(6)
C COMMON RRHUB(6), RC(6), RBLADE(6), STAGER(6)
C COMMON SHUB(7), SC(7), SBLADE(7), STAGES(7)
C COMMON SIGUR(6), BETISR(6), BETSSR(6), AINS(6), ADEVS(6)
C COMMON SIGURS(7), BETISSR(7), BETISSS(7), AINS(7), ADEVS(7)
C COMMON UTPG(6), UTP(6), UTP2(6), UUMA(6), UHUB(6), UFAI
C COMMON AREA(6), AREAS(7), UU2(6), UUM2(6), UHUB2(6), IPRT
C COMMON ICENT, ICENT, MR(6), MA(6), IDES, FAID
C COMMON NS, NSSL, RT(6), RH(6), ST(6), SM(6), SH(6)
C COMMON DSS, AAIN(7), AREA(7), PM120(6), PM130(6), ETAR(6)
C COMMON DR(6), DS(6), DEQ(6), DEOS(6), BLOCK(6), BLOCKS(7)
C COMMON BET(6), BETAMR(6), BBM(7), BBMS(7), RAD(6), RAD(7)
C DIMENSION D(20, 3), XA(20, 3), XR(20, 3)
C DIMENSION WS(3), WMASS(3), VMASS(3), RHA(3), RHOM(3), TB(3)
C DIMENSION DEL2(6), ETA(6)
C DIMENSION XAX(3), XXU(3), DAUE(20)
C DIMENSION TME(3)
C DIMENSION DTWAR(20), JMASS(3), HTMP(3)
C DIMENSION DTM(3), QMASS(3), XAIR(3), XMTAN(3), XGAS(3), FAIST(6)
C DIMENSION DELB(7), DELB(7), XGBL(7), XGBL(7), XGBL(7)
C****************************************************************************** MAIN 50
C****************************************************************************** MAIN 51
C READ INPUT DATA
C****************************************************************************** MAIN 55

READ(99, NS)
99 FORMAT(1I)
NS = N5 + 1
READ(100, GSF)
100 FORMAT(1I1)
READ(101, GSF(3))
101 FORMAT(1I3)
READ(111, GSF(3))
111 FORMAT(1I3)
READ(112, GSF(2))
112 FORMAT(1I2)
READ(113, GSF(2))
113 FORMAT(1I2)
READ(114, GSF(2))
114 FORMAT(1I2)
READ(115, SC(1), I1, I7)
115 FORMAT(1I2)
READ(5,1512) (SAREAS(I),I=1,NS1)

1512 FORMAT(7F10.7) MAIN 141
1513 FORMAT(6F8.2) MAIN 142
1514 FORMAT(7F10.7) MAIN 143
1515 FORMAT(6F8.2) MAIN 144
1516 FORMAT(6F8.2) MAIN 145
1517 FORMAT(6F8.2) MAIN 146
1518 FORMAT(6F8.2) MAIN 147
1519 FORMAT(6F8.2) MAIN 148
1520 FORMAT(7F10.7) MAIN 149
1521 FORMAT(6F8.2) MAIN 150
1522 FORMAT(6F8.2) MAIN 151
1523 FORMAT(6F8.2) MAIN 152
1524 FORMAT(6F8.2) MAIN 153
1525 FORMAT(6F8.2) MAIN 154
1526 FORMAT(6F8.2) MAIN 155
1527 FORMAT(6F8.2) MAIN 156
1528 FORMAT(6F8.2) MAIN 157
1529 FORMAT(6F8.2) MAIN 158
1530 FORMAT(6F8.2) MAIN 159
1531 FORMAT(6F8.2) MAIN 160
1532 FORMAT(6F8.2) MAIN 161
1533 FORMAT(6F8.2) MAIN 162
1534 FORMAT(6F8.2) MAIN 163
1535 FORMAT(6F8.2) MAIN 164
1536 FORMAT(6F8.2) MAIN 165
1537 FORMAT(6F8.2) MAIN 166
1538 FORMAT(6F8.2) MAIN 167
1539 FORMAT(6F8.2) MAIN 168
1540 FORMAT(6F8.2) MAIN 169
1541 FORMAT(6F8.2) MAIN 170
1542 FORMAT(6F8.2) MAIN 171
1543 FORMAT(6F8.2) MAIN 172
1544 FORMAT(6F8.2) MAIN 173
1545 FORMAT(6F8.2) MAIN 174
1546 FORMAT(6F8.2) MAIN 175
1547 FORMAT(6F8.2) MAIN 176
1548 FORMAT(6F8.2) MAIN 177
1549 FORMAT(6F8.2) MAIN 178
1550 FORMAT(6F8.2) MAIN 179
1551 FORMAT(6F8.2) MAIN 180
1552 FORMAT(6F8.2) MAIN 181
1553 FORMAT(6F8.2) MAIN 182
1554 FORMAT(6F8.2) MAIN 183
1555 FORMAT(6F8.2) MAIN 184
1556 FORMAT(6F8.2) MAIN 185
1557 FORMAT(6F8.2) MAIN 186
1558 FORMAT(6F8.2) MAIN 187
1559 FORMAT(6F8.2) MAIN 188
1560 CONTINUE MAIN 189
1561 CONTINUE MAIN 190
1562 CONTINUE MAIN 191
1563 CONTINUE MAIN 192
1564 CONTINUE MAIN 193
1565 CONTINUE MAIN 194
1566 CONTINUE MAIN 195
1567 CONTINUE MAIN 196
1568 CONTINUE MAIN 197
1569 CONTINUE MAIN 198
1570 CONTINUE MAIN 199
1571 CONTINUE MAIN 200
1572 CONTINUE MAIN 201
1573 CONTINUE MAIN 202
1574 CONTINUE MAIN 203
1575 CONTINUE MAIN 204
1576 CONTINUE MAIN 205
1577 CONTINUE MAIN 206
1578 CONTINUE MAIN 207
1579 CONTINUE MAIN 208
1580 CONTINUE MAIN 209
1581 CONTINUE MAIN 210
1801 FORMAT(IH,1X,RT(I)*,EX,6(F5.3,1X))
WRITE(6,1802) (RM(I),I=1,NS)
WRITE(6,1803) (RH(I),I=1,NS)
1804 FORMAT(IH,1X,RH(I)*,EX,6(F5.3,1X))
WRITE(6,1804) (ST(I),I=1,NS)
1805 FORMAT(IH,1X,SM(I)*,EX,6(F5.3,1X))
WRITE(6,1805) (SH(I),I=1,NS)
1806 FORMAT(IH,1X,SH(I)*,EX,6(F5.3,1X))
WRITE(6,1807) (BLOCK(I),I=1,NS)
1807 FORMAT(IH,1X,BLOCK(I)*,EX,6(F5.3,1X))
WRITE(6,1808) (BLOCKS(I),I=1,NS)
1808 FORMAT(IH,1X,BLOCKS(I)*,EX,6(F5.3,1X))
WRITE(6,1810) (BET2MS(I),I=1,NS)
1810 FORMAT(IH,1X,BET2MS(I)*,EX,6(F5.3,1X))
WRITE(6,1811) (BET2MR(I),I=1,NS)
1811 FORMAT(IH,1X,BET2MR(I)*,EX,6(F5.3,1X))
WRITE(6,1812) (BETMR(I),I=1,NS)
1812 FORMAT(IH,1X,BETMR(I)*,EX,6(F5.3,1X))
WRITE(6,1813) (BETMS(I),I=1,NS)
1813 FORMAT(IH,1X,BETMS(I)*,EX,6(F5.3,1X))
WRITE(6,1814) (BET2HH(I),I=1,NS)
1814 FORMAT(IH,1X,BET2HH(I)*,EX,6(F5.3,1X))
WRITE(6,1815) (PRID(I),I=1,NS)
1815 FORMAT(IH,1X,PRID(I)*,EX,6(F5.3,1X))
WRITE(6,1816) (PRI3D(I),I=1,NS)
1816 FORMAT(IH,1X,PRI3D(I)*,EX,6(F5.3,1X))
WRITE(6,1817) (ETARD(I),I=1,NS)
1817 FORMAT(IH,1X,ETARD(I)*,EX,6(F5.3,1X))
1818 FORMAT(IH,1X,FMX,**********INPUT DATA**********)
WRITE(6,1820) (RT(I),I=1,NS)
1820 FORMAT(IH,1X,RT(I)*,EX,6(F5.3,1X))
WRITE(6,1821) (RM(I),I=1,NS)
1821 FORMAT(IH,1X,RM(I)*,EX,6(F5.3,1X))
WRITE(6,1822) (RH(I),I=1,NS)
1822 FORMAT(IH,1X,RH(I)*,EX,6(F5.3,1X))
WRITE(6,1823) (SH(I),I=1,NS)
1823 FORMAT(IH,1X,SH(I)*,EX,6(F5.3,1X))
WRITE(6,1824) (SM(I),I=1,NS)
1824 FORMAT(IH,1X,SM(I)*,EX,6(F5.3,1X))
WRITE(6,1825) (RT(I),I=1,NS)
1825 FORMAT(IH,1X,RT(I)*,EX,6(F5.3,1X))
WRITE(6,1826) (BD(I),I=1,NS)
1826 FORMAT(IH,1X,BD(I)*,EX,6(F5.3,1X))
WRITE(6,1827) (DHI,DIH)
1827 FORMAT(IH,1X,DHI,DIH)
WRITE(6,1828) (HD(I),I=1,NS)
1828 FORMAT(IH,1X,HD(I)*,EX,6(F5.3,1X))
WRITE(6,1829) (DHI,DIH)
1829 FORMAT(IH,1X,DHI,DIH)
WRITE(6,1830) (TIM(I),I=1,NS)
1830 FORMAT(IH,1X,TIM(I)*,EX,6(F5.3,1X))
WRITE(6,1831) (DSM(I),I=1,NS)
1831 FORMAT(IH,1X,DSM(I)*,EX,6(F5.3,1X))
WRITE(6,1832) (RD(I),I=1,NS)
1832 FORMAT(IH,1X,RD(I)*,EX,6(F5.3,1X))
WRITE(6,1833) (VCI,1X)
1833 FORMAT(IH,1X,VCI,1X)
WRITE(6,1834) (FCRMAT(I),I=1,NS)
1834 FORMAT(IH,1X,FCRMAT(I)*,EX,6(F5.3,1X))
WRITE(6,1835) (COMPRESSOR INLET TOTAL TEMPERATURE OF GAS)=#.
1835 FORMAT(IH,1X,COMPRESSOR INLET TOTAL TEMPERATURE OF GAS)=#.
WRITE(6,1836) (COMPRESSOR INLET TOTAL PRESSURE)=#.
1836 FORMAT(IH,1X,COMPRESSOR INLET TOTAL PRESSURE)=#.
WRITE(6,1837) (INLET TEMPERATURE OF DROPLET)=#.
1837 FORMAT(IH,1X,INLET TEMPERATURE OF DROPLET)=#.
WRITE(6,1838) (COMPRESSOR INLET TATUM PRESSURE)=#.
1838 FORMAT(IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1839) (INLET TEMPERATURE OF DROPLET)=#.
1839 FORMAT(IH,1X,INLET TEMPERATURE OF DROPLET)=#.
WRITE(6,1840) (INLET TEMPERATURE OF DROPLET)=#.
1840 FORMAT(IH,1X,INLET TEMPERATURE OF DROPLET)=#.
WRITE(6,1841) (COMPRESSOR INLET TATUM PRESSURE)=#.
1841 FORMAT(IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1842) (COMPRESSOR INLET TATUM PRESSURE)=#.
1842 FORMAT(IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1843) (COMPRESSOR INLET TATUM PRESSURE)=#.
1843 FORMAT(IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1844) (COMPRESSOR INLET TATUM PRESSURE)=#.
1844 FORMAT(IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1845) (COMPRESSOR INLET TATUM PRESSURE)=#.
1845 FORMAT(IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1846) (COMPRESSOR INLET TATUM PRESSURE)=#.
1846 FORMAT(IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1847) (COMPRESSOR INLET TATUM PRESSURE)=#.
1847 FORMAT(IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1848) (COMPRESSOR INLET TATUM PRESSURE)=#.
1848 FORMAT(IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1849) (COMPRESSOR INLET TATUM PRESSURE)=#.
1849 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1850) (COMPRESSOR INLET TATUM PRESSURE)=#.
1850 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1851) (COMPRESSOR INLET TATUM PRESSURE)=#.
1851 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1852) (COMPRESSOR INLET TATUM PRESSURE)=#.
1852 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1853) (COMPRESSOR INLET TATUM PRESSURE)=#.
1853 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1854) (COMPRESSOR INLET TATUM PRESSURE)=#.
1854 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1855) (COMPRESSOR INLET TATUM PRESSURE)=#.
1855 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1856) (COMPRESSOR INLET TATUM PRESSURE)=#.
1856 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1857) (COMPRESSOR INLET TATUM PRESSURE)=#.
1857 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1858) (COMPRESSOR INLET TATUM PRESSURE)=#.
1858 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1859) (COMPRESSOR INLET TATUM PRESSURE)=#.
1859 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1860) (COMPRESSOR INLET TATUM PRESSURE)=#.
1860 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1861) (COMPRESSOR INLET TATUM PRESSURE)=#.
1861 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
WRITE(6,1862) (COMPRESSOR INLET TATUM PRESSURE)=#.
1862 Format (IH,1X,COMPRESSOR INLET TATUM PRESSURE)=#.
RRTIP(I)=RRTIP(I)/CFL
RT(I)=RT(I)/CFL
RM(I)=RM(I)/CFL
RH(I)=RH(I)/CFL
ST(I)=ST(I)/CFL
SM(I)=SM(I)/CFL
SH(I)=SH(I)/CFL
SAREA(I)=SAREA(I)/CFA
156 CONTINUE
DO 157 I=1,NS1
SRHUB(I)=SRHUB(I)/CFL
SC(I)=SC(I)/CFL
SRTIP(I)=SRTIP(I)/CFL
SAREAS(I)=SAREAS(I)/CFA
157 CONTINUE
TG=TOG/CFT
TOW=TOW/CFT
PO=P0/CFP
TO1D=TO1D/CFT
PO1D=PO1D/CFP
DSNASS=DSNASS/CFM
852 CONTINUE
COTHER INPUT DATA
WKDONE=1.0
IPRINT=1
DO 153 I=1,NS
FNRI(I)=0.6
FNRA(I)=0.6
153 CONTINUE
AK1=1.0
AK2=1.0
AK3=1.0
AAAIGU=SAREA(1)
RU=1545.3
RHOJ=62.54
CPW=1.00
PAI=3.1415926
DO 150 I=1,MS
AAREA(I)=PAI*(RRTIP(I)/12.0)**2-(SRHUB(I)/12.0)**2)*BLOCK(I)
AAREAS(I)=PAI*(SRTIP(I)**2-SRHUB(I)**2)/144.0*BLOCKS(I)
DELZ(I)=(RC(I)+SC(I))/12.0
150 CONTINUE
NSI=NS1
AAREA(NSI)=PAI*(SRTIP(NSI)**2-SRHUB(NSI)**2)/144.0*BLOCKS(NSI)
AAARIT=AAREA(1)
DO 152 I=1,NS
AREA(I)=SAREA(I)
AREAS(I)=SAREAS(I)
152 CONTINUE
AREA(NSI)=SAREAS(NSI)
TO1G=TOG
TO1D=TOW
PO1D=PO
DO 151 I=1,NS
UTIP(I)=RT(I)/12.0*2.0*PAI*FND/60.0
UTIPG(I)=RT(I)/12.0*2.0*PAI*FND/60.0
UTIP2(I)=ST(I)/12.0*2.0*PAI*FND/60.0
UTIPD(I)=RT(I)/12.0*2.0*PAI*FND/60.0
UOU(I)=(UTIP(I)/UTIPD(I))**2
UMEAN(I)=RM(I)/12.0*2.0*PAI*FND/60.0
UMEAN2(I)=SM(I)/12.0*2.0*PAI*FND/60.0
191


```
UMUB(I)=RH(I)/12.0*2.0*PAI*FMD/60.0
UMUB2(I)=SH(I)/12.0*2.0*PAI*FMD/60.0
IF(IRAD.EQ.1) U(I)=UTIP(I)
IF(IRAD.EQ.2) U(I)=UMEAN(I)
IF(IRAD.EQ.3) U(I)=UHUB(I)
IF(IRAD.EQ.1) UU2(I)=UTIP2(I)
IF(IRAD.EQ.2) UU2(I)=UMEAN2(I)
IF(IRAD.EQ.3) UU2(I)=UHUB2(I)
IF(IRAD.EQ.1) RADII(I)=RT(I)
IF(IRAD.EQ.2) RADII(I)=SM(I)
IF(IRAD.EQ.3) RADII(I)=SH(I)
151 CONTINUE

MAIN

C------------------------------------------

C BLADERESETTING
DO 154 I=1,NS
BET1MR(I)=BET1MR(I)+DELB1R(I)
BET2MR(I)=BET2MR(I)+DELB1R(I)
STAGRE(I)=STAGRE(I)+DELB1R(I)
BET1MS(I)=BET1MS(I)+DELB1S(I)
BET2MS(I)=BET2MS(I)+DELB1S(I)
STAGES(I)=STAGES(I)+DELB1S(I)
154 CONTINUE

TG(I)=TOID
P(I)=POID
CALL WICSPD(DMSAS,ISTAGE)

C C C C

C RORER SPEED AND RADIUS
C
C

C C C C

DO 155 I=1,NS
UTIP(I)=RT(I)/12.0*2.0*PAI*FN/60.0
UTIPG(I)=RTIP(I)/12.0*2.0*PAI*FN/60.0
UTIPG(I)=ST(I)/12.0*2.0*PAI*FN/60.0
UTIPG(I)=RT(I)/12.0*2.0*PAI*FN/60.0
UUU(I)=(UTIP(I)-UTIPD(I))**2
UMEAN(I)=RM(I)/12.0*2.0*PAI*FN/60.0
UMEAN2(I)=SM(I)/12.0*2.0*PAI*FN/60.0
UMUB(I)=RH(I)/12.0*2.0*PAI*FN/60.0
UMUB2(I)=SH(I)/12.0*2.0*PAI*FN/60.0
IF(IRAD.EQ.1) U(I)=UTIP(I)
IF(IRAD.EQ.2) U(I)=UMEAN(I)
IF(IRAD.EQ.3) U(I)=UHUB(I)
IF(IRAD.EQ.1) UU2(I)=UTIP2(I)
IF(IRAD.EQ.2) UU2(I)=UMEAN2(I)
IF(IRAD.EQ.3) UU2(I)=UHUB2(I)
IF(IRAD.EQ.1) RADII(I)=RT(I)
IF(IRAD.EQ.2) RADII(I)=SM(I)
IF(IRAD.EQ.3) RADII(I)=SH(I)
155 CONTINUE

C ++++++++++++++++++++++++++++++++++++++++ C

C MASS FLOE RATE
C
C

C C C C

901 READ(5#200) FAI
200 FORMAT(F7.5)
917 FORMAT(1H1,2X,#FAI=#,F7.5)
```

192
FAI0=FAI
U2=UTIPG(1)*FAI
TG(1)=OT01G
UZERO=0.0
UZERO=0.0
RZERO=RRHUB(1)
RZERO=RRHUB(1)
ITIP=0
ITIP=0
DAUE(N)=0.0
DDAUE(N)=0.0
TW(1)=DTOID
TLJW(1)=TOTO1U
IF(XDIM.GT.0.0) IF(XDDIM.GT.0.0)
T(1)=Oi~1D
F()=DIN
RHOAG(I)=PC(I)/RA
RHOA(I)=PC(I)
AAA=AAI
AAA3=AAA IGV
CA=ALLWCAISTMSMT()PlMUZCXJC)ITS(S
CALLX,
GRMOI)=1C0+2*IX2*43*RAG31
RHOM(1)=.(1.0-XWT(1))*CRHOG(1)xTIRa)
RMSS=RHOM(1.0FAI*TI(l)
MMASS=MMASO*XDIN
WMASO=1.MASXINMSOM1
5558
FORMAT(100.2X,4(F10.5,2X))
DAMY=OT01G/518.7
DAMY2=OP01/14.7*144.0
CHASS=MASS*SORT(DAMY)/DAMY2
AMASS = XA = MASS
UMASS(1)=XU(1)*MMASS
UMASS(1)=XU(1)*MMASS
UMASS(1)=XU(1)*MMASS
CMASS=XXIMASS
GMASS=MASS-Umass(1)
CHASS2=CHASS(1)*SORT(DAMY)/DAMY2
AI0=MASS
LMD=MASS(1)
CMASS(1)
GM=MASS(1)
LMD=MASS(1)
LMD=MASS(1)
LMD=MASS(1)
LMD=MASS(1)
C MAIN 561

C MAIN 562

C MAIN 563

C MAIN 564

C MAIN 565

C MAIN 566

C MAIN 567

C MAIN 568

C MAIN 569

C MAIN 570

C MAIN 571

C MAIN 572

C MAIN 573

C MAIN 574

C MAIN 575

C MAIN 576

C MAIN 577

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C MAIN 618

C MAIN 619

C MAIN 620

C MAIN 621

C MAIN 622

C MAIN 623

C MAIN 624

C MAIN 625

C MAIN 626

C MAIN 627

C MAIN 628

C MAIN 629

C MAIN 630
IF(IPERFM.EQ.1) JPERFM=1
IF(IPERFM.EQ.2) JPERFM=2
IF(IPERFM.EQ.3) JPERFM=3
DAMY=0.0
IF(UHMASS(1)*GT.1.0E-4)
SDAMYN=WUMASS(1)/WTMASS(1)
*IF(DAY1.GT.0.20) JPERFM=3
IF(IPRINT.EQ.2) WRITE(6*8000) JPERFM
*8000 FORMAT(1N0,S81STAGE PERFORMANCE CALCULATION(JPERFM=\#12\#0)
1300 CALL WICSPA(FAI0,ISTAGE,MMASS,ALFA1,WKDONE,DAME(1),XMIN,ETA,
$BETA1,BETA2,VZ,ALFA2,ALFA3,DELTG,DELTW,W1,W2,U1,U2,23,A1,A3)
GO TO 1303
1301 CALL WICSPB(FAI0,ISTAGE,MMASS,ALFA1,WKDONE,DAME(1),DELV,WMASS(1)
$N,OMEGA1,
$ORCA2,OMEGA3,OMEGA4,OMEGA5,OMEGA6,OMEGAT,BETA1,BETA2,VZ,ALFA2,
$ALFA3,DELTG,DELTW,W1,W2,U1,U2,23,A1,A2,A3)
GO TO 1303
1302 CALL WICSCP(FAI0,ISTAGE,MMASS,ALFA1,WKDONE,DAME(1),DELV,WMASS(1)
$I,WMASS(1),N,OMEGA1,
$OMEG2,OMEGA3,OMEGA4,OMEGA5,OMEGA6,OMEGAT,BETA1,BETA2,UZ,ALFA2,
$ALFA3,DELTG,DELTW,W1,W2,U1,U2,23,REVE,DELUL,23,AK1,AK2,AK3)
1303 CONTINUE
DELTG1=DELTG
DELTW1=DELTW
IF(UZ.LT.0.0.OR.VZ.GT.1000.0) WRITE(6*8010) LIZ
8010 FORMAT(IH190*AXIAL VELOCITY IS TOO HIGH OR TOO LOW,\#UZ=\#
$F10.5)
AAA2=AREAS(ISTAGE)
AAA3=AREA(ISTAGE+1)
IF(ISTAGE.EQ.MS) AAA3=AAA2
AAA1=AAA2
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AAA2=AAA3
AAA3=AAA1
AAA1=AAA2
AAA2=AAA3
AAA3=AAA1
AAA1=AAA2
AAA2=AAA3
AAA3=AA
BMWAKR = BMIMPR *(1.0 - PREB/100.0)
BMINOR = WMASS(1) - BMWAKR
X4WB = 0.0
IF (WMASS(1).GT.1.0E-6) WMID = BMWAKR/WMASS
X4WAX = BMINOR/WMASS
X4WAR = BMWAKR/WMASS
IF (IPRINT.EQ.2) WRITE(6,6090) BMIMPR, BMREBR, BMWAKR, BMINOR, X4WAR.
$X4WAR = X4WAX
6090 FORMAT(1H7(F12.5))
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**Documentation**

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**Variables and Equations**

- $X_{G} = X_{A} + X_{U} + X_{C}$
- $X_{AIR} = X_{A}$
- $X_{RETAN} = X_{CH_{4}}$
- $X_{GAS} = X_{G}$
- $P_{1} = \frac{L_{S} P}{W S_{40.6219}}$
- $\text{CALL IICPRP}(X_{A}, X_{U}, X_{CH_{4}}, T_{G}, \text{PRMIX}, \text{CPMIX}, \text{GAMMA}, \gamma_{1}, \gamma_{2}, \gamma_{3})$
- $\rho_{G} = \frac{P}{\rho_{M_{\text{MIX}}}}$
- $\text{IF}(J_{\text{PERFM}} \neq 3) B_{\text{MSS}} = M_{\text{MSS}}$
- $\text{IF}(J_{\text{PERFM}} = 3) B_{\text{MSS}} = G_{\text{MSS}}(2)$
- $\text{CALL WICMAC}(I_{\text{STAGE BIAS}}, P, U_{Z}, C_{XU}, T, \text{L}, \text{CPMIX}, \text{AAA}, \gamma_{2})$
- $\rho_{G} = \left(1.0 + \gamma_{2} \frac{J_{1}^{2}}{J_{1}}\right)^{2} \rho_{G_{C}}$
- $\rho_{M} = \left(1.0 - X_{W_{T}}\right) \rho_{G} + X_{W_{T}} \rho_{I}$
- $\rho_{A} = \left(1.0 + \gamma_{2} \frac{J_{1}^{2}}{J_{1}}\right)^{2} \rho_{A_{C}}$
- $\text{IF}(I_{\text{PRINT}} \leq 2) \text{WRITE}(6, 614)$
- $U_{Z}, V_{A}, D_{1}, D_{2}, D_{3}, W_{T_{\text{MSS}}}(2), M_{\text{MSS}}(2), U_{Z}(2)$
- $614 \text{FORMAT}(10, \text{F12.5}, 1 \times)\text{X}$
- $\text{IF}(I_{\text{PRINT}} \geq 2) \text{WRITE}(6, 615)$
- $\rho_{M}, \rho_{A}, \rho_{C}$
- $615 \text{FORMAT}(10, \text{F12.5})$
- $U_{Z}$ is too high or too low: $U_{Z} = \#F10.4$
- $\text{CENTRIFUGAL ACTION IN ROTOR}$
- $\rho_{G_{S}} = \rho_{G}(2)$
- $\rho_{H_{B}} = \rho_{H_{B}}(\text{ISTAGE})$
- $\text{CALL WICDMS}(I_{\text{PRINT}}, I_{\text{RAD}}, W_{\text{MSS}}, A_{\text{MSS}}(2), A_{\text{MSS}}(2), D_{\text{LSS}}(2), D_{\text{LSS}}(2))$
- $WC_{\text{CENT}} = D_{\text{LSS}}(2)$
- $U_{Z}(2), U_{2}$
- $996 \text{DEL}_{M} = \text{DEL}_{M}$

**Conditional Statements**

- $\text{IF}(\text{WT}_{MSS}(1) \geq 1.0 \times 10^{-6})$ $\rho_{H} = \rho_{M_{\text{MSS}}(1)} / \rho_{M_{\text{MSS}}(1)}$
- $\text{IF}(\text{WT}_{MSS}(1) \geq 1.0 \times 10^{-6})$ $\rho_{M_{\text{MSS}}(1)} = \rho_{M_{\text{MSS}}(1)}$
- $\text{AMAS}_{W} = (\text{UM}_{\text{MSS}} - \text{UC}_{\text{CENT}} - \text{LA}_{\text{CENT}}) \times \rho_{W}$
- $\text{EMAS}_{W} = (\text{J}_{\text{IA}_{\text{MSS}}} - \text{W}_{\text{CENT}} - \text{W}_{\text{WC}_{\text{CENT}}}) \times \rho_{W}$
- $\text{IF}(D_{\text{AVE}(N-1)} \leq 1.0 \times 10^{-6})$ GO TO 999
- $\text{IF}(D_{\text{AVE}(N-1)} \geq 1.0 \times 10^{-6})$ Go to 996
- $D_{\text{AV}_{\text{E}(N-1)}} = D_{\text{AV}_{\text{E}(N-1)}}$
- $D_{\text{AV}_{\text{E}(N-1)}} = D_{\text{AV}_{\text{E}(N-1)}}$
- $D_{\text{AV}_{\text{E}(N-1)}} = D_{\text{AV}_{\text{E}(N-1)}}$
- $D_{\text{AV}_{\text{E}(N-1)}} = D_{\text{AV}_{\text{E}(N-1)}}$
- $\text{IF}(D_{\text{AV}_{\text{E}(N-1)}}, D_{\text{AV}_{\text{E}(N-1)}} = D_{\text{AV}_{\text{E}(N-1)}}$
- $D_{\text{AV}_{\text{E}(N-1)}} = D_{\text{AV}_{\text{E}(N-1)}}$
- $D_{\text{AV}_{\text{E}(N-1)}} = D_{\text{AV}_{\text{E}(N-1)}}$
- $\text{IF}(D_{\text{AV}_{\text{E}(N-1)}}, D_{\text{AV}_{\text{E}(N-1)}} = D_{\text{AV}_{\text{E}(N-1)}}$
- $D_{\text{AV}_{\text{E}(N-1)}} = D_{\text{AV}_{\text{E}(N-1)}}$
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- $D_{\text{AV}_{\text{E}(N-1)}} = D_{\text{AV}_{\text{E}(N-1)}}$
CALL WICCEN(RZERO, UZERO, I0, UZ, DELZ, ALFAU, FN, IRS, RHOAS, RRTIP(ISTAGE)), MAIN 911
CALL WICIIU(I0, UZ, XG, XH(2), CH4, RRTIP(ISTAGE)), MAIN 912
CALL WICIDU(I0, UZ, XM1, XM2, DELX, RZERO, RZ, AREA(IS
STAGE), RADI(IS), RRTIP(ISTAGE), XMIN, XOUT, AMAS2, DELMAS) MAIN 913
RZERO=R2 MAIN 914
UZERO=U2 MAIN 915
9996 DELMA=DELMS MAIN 916
WMD=WMAS(2) MAIN 917
WMAS(2)=WMAS(2)+DELMA MAIN 918
WMAS(2)=WMAS(2)+DELMA MAIN 919
IF(WMAS(2).GT.WMASL) TT=WMAS(2)/WMASL MAIN 920
IF(WMAS(2).GT.WMASL) WMAS(2)=WMAS(2)/TT MAIN 921
IF(WMAS(2).GT.WMASL) WMAS(2)=WMAS(2)/TT MAIN 922
DELMA=DELMAS(2)-WMD MAIN 923
WMAS(2)=WMAS(2)+WMAS(2) MAIN 924
WMAS(2)=WMAS(2)-WTMAS(1) MAIN 925
WMAS(2)=WMAS(2)-WTMAS(1) MAIN 926
WMAS(2)=WMAS(2)-WTMAS(1) MAIN 927
WMAS(2)=WMAS(2)-WTMAS(1) MAIN 928
WMAS(2)=WMAS(2)-WTMAS(1) MAIN 929
WMAS(2)=WMAS(2)-WTMAS(1) MAIN 930
WMAS(2)=WMAS(2)-WTMAS(1) MAIN 931
XM1=XMAS(2)-CH4 MAIN 932
XM1=XMAS(2)-CH4 MAIN 933
XM1=XMAS(2)-CH4 MAIN 934
XM1=XMAS(2)-CH4 MAIN 935
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XM1=XMAS(2)-CH4 MAIN 978
XM1=XMAS(2)-CH4 MAIN 979
XM1=XMAS(2)-CH4 MAIN 980
C STATOR WAKE

IF(IPRINT.EQ.2) WRITE(6,8080)

8080 FORMAT(IHO,* STATOR WAKE*)

M=M+1
ALFA=ALFA3
AWAKEM=0.0
IF(AMWAKS.GT.0.0) GO TO 632
GO TO 633

632 CALL WICWAK(RHOG(2),U3,DIWAKE,DWAKEN)

633 D1=DWAKEM
IF(D1.LT.0.0) D1=0.0
IF(D1.GT.DIN) D1=DIN
AMING1=AMWAKS
ALFA=ALFA3
SEDLU=DELULU2
DWAKEM=0.0
IF(AMWAKS.GT.0.0) GO TO 6330
GO TO 6331

6330 CALL WICWAK(RHOG(2),SEDLU1,DIWAKE,DWAKEN)

6331 D2=DWAKEM
IF(D2.LT.0.0) D2=0.0
IF(D2.GT.DIN) D2=DIN
SUP2=(90.0-ALFA3)/180.0
AMING2=AMWAKS*SUP2
SEDLU=DELUL2
DWAKEM=0.0
IF(AMWAKS.GT.0.0) GO TO 6332
GO TO 6333

6332 CALL WICWAK(RHOG(2),SEDLU2,DIWAKE,DWAKEN)

6333 D3=DWAKEM
IF(D3.LT.0.0) D3=0.0
IF(D3.GT.DIN) D3=DIN
SUP2=(90.0+ALFA3)/180.0
AMING3=AMWAKS*SUP2
UWMASS=WMASS(2)-AMWAKS
UWMASSL=WMASS(2)-AMWAKS
IF(UWMASS.LT.0.0) WMASS=0.0
IF(UWMASSL.LT.0.0) WMASSL=0.0
CALL WICSIZ(UWMASS,WMASS,AMING1,AMING2,AMING3,DWAKE(2),DIWAKE(2),DIWAKE(2),D1,D2,D3,DLIMIT,ALGEC,DLGEC,DLILE)

WMASS(3)=AMLGE
WMASSL(3)=AMLGE
IF(WMASS(3).LT.0.0) WMASS(3)=0.0
IF(WMASSL(3).LT.0.0) WMASSL(3)=0.0
WTMASS(3)=WMASS(2)+WMASS(2)
UMASS=AMASS+UMASS(3)+WTMASS(3)
TMASS(3)=UMASS
WMASS(3)=TMASS(3)-WTMASS(3)
DWAUE(N)=DLILE
DWAUE(N)=DLGEC
XU(3)=UMASS(3)/UMASS
XU(3)=UMASS(3)/UMASS
XU(3)=TMASS(3)/UMASS
XU(3)=XU(2)
X=AMASS/UMASS
XC4=CHMASS*UMASS
XG=X+XU(3)+XCH4
XAIR(3)=X
XMETAN(3)=XCH4
XGAS(3)=XG
IF(WMASS(3).LT.1.0E-6) WMASS=UMASS(3)
IF(WMASSL(3).LT.1.0E-6) WMASSL=UMASSL(3)
IF(WMASS(3).GT.0.0) RH=AMASS(3)/WMASS(3)
IF(WMASS(3).GT.0.0) RW=AMASS(3)/WMASS(3)
TG(3)=TG(2)

200
T(3)=T(2) 

IF(IPRINT.EQ.2) WRITE(6,619) RHODA(2),UZ,ALFA,D1,D2,UMASS(3) 

619 FORMAT((H,10(F12.5,1X)) 

IF(IPRINT.EQ.2) WRITE(6,620) DAUE(N),TG(3),TH(3) 

620 FORMAT(1HO0 HEAT TRANSFER) 

HEAT TRANSFER (SMALL DROPLET) 

IF(IPRINT.EQ.2) WRITE(6,8120) 

8120 FORMAT(IH0,* HEAT TRANSFER*) 

DELTHG=0.0 

IF(DAVE(N-2).GT.0.0.AND.DAVE(N).GT.0.0) GO TO 8121 

8121 RE=0.0 

8122 DELTG2=DELTH 

DELTG2=DELTH 

C HEAT TRANSFER (LARGE DROPLET) 

DELTHG=0.0 

DELTHG=0.0 

IF(DAVE(N-2).GT.0.0.AND.DAVE(N).GT.0.0) GO TO 8123 

8123 RE=0.0 

201
\[ \text{CCP} = \text{CPG}1 + \text{CPG}3 / 2.0 \]

CALL WICET(TG(1), TG(3), TW(1), TW(3), DDAVE(N-2), DDAVE(N))

\$ DEL2(ISTAGE), UZ, WMAS1, WMAS3, AMAS3, CHMAS3, CPW, CPH, DELTG

\$ DELTH, RE)

\[ \text{MAIN 1124} \]

DELTG3 = DELTG

DELTH3 = DELW

TG(3) = TG(1) + DELTG1 - DELTG2 - DELTG3

TW(3) = TW(1) + DELTW1 + DELTW2

TRATIO = TG(3) / TG(1)

IF(IPRINT.EQ.2) WRITE(6,627) DELTG2, DELTU2, DELTG3, DELTU3, TG(3), STW(3), TWW(3), TRATIO

627 FORMATT(6,627) DELTG2, DELTU2, DELTG3, DELTU3

C MASS TRANSFER CALCULATION

IF(IPRINT.EQ.2) WRITE(GP8130) MASS TRANSFER$

DAUEN2 = DDAUE(N-2)

DAUEN = DDAUE(N)

DZ = DELZ(ISTAGE)

RE = 0.0

DMDTAU = 0.0

IF(DAUE(N-2).GT.0.0.AND.DAUE(N).GT.0.0) GO TO 636

GO TO 637

636 CALL WICMAS(HS(1), TH(1), TH(3), P(1), P(3), TG(1), TG(3), DZ, PW1, PW2

\$ PH1, PH2, UZ, DAUEN, DAUE, H2, WMAS1, WMAS3, WMAS5, WMAS7

\$ WMAS2, WMAS4, WMAS6, WMAS8, WMAS, RE)

637 DMDTA1 = DMDTAU

IF(DMDTA1.LT.0.0) DMDTA1 = 0.0

DAUEN = DAUE(N-2)

DAUEN = DAUE(N)

DZ = DELZ(ISTAGE)

RE = 0.0

DMDTAU = 0.0

IF(DAUE(N-1).GT.0.0.AND.DAUE(N).GT.0.0) RE = REAVE

IF(DAUE(N-2).GT.0.0.AND.DAUE(N).GT.0.0) GO TO 6360

GO TO 6370

6360 CALL WICMAS(HS(1), TH(1), TH(3), P(1), P(3), TG(1), TG(3), DZ, PW1, PW2

\$ PH1, PH2, UZ, DAUEN, DAUE, H2, WMAS1, WMAS3, WMAS5, WMAS7

\$ WMAS2, WMAS4, WMAS6, WMAS8, WMAS, RE)

6370 DMDTA2 = DMDTAU

IF(DMDTA2.LT.0.0) DMDTA2 = 0.0

WMAS3 = WMAS(3) - DMDTA1

WMAS(3) = WMAS(3) + DMDTA2

WMAS3 = WMAS(3) + WMAS(3) - DMDTA2

IF(WMASLT.LT.0.0) WMASLT = 0.0

IF(WMAS(3).LT.0.0) WMAS(3) = 0.0

IF(WMAS(3).LT.0.0) WMAS(3) = 0.0

WMAS3 = WMAS(3) + WMAS(3)

WMAS3 = WMAS(3) + WMAS3 - DMDTA2

WMAS = WMAS + CHMAS + WMAS3 - WMAS(3)

TMAS3 = WMAS

\$ WMAS(3) = WMAS(3) - WMAS(3)

XX(3) = WMAS3 / WMAS

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RHOA(3) = P(3)/RA/TC(3) MAIN 1191
CALL WILPRP(XA.X(3)PXCH4T(3)RIIXCPIIXPAMMtAG162,G3) MAIN 1192
RHOC(3) = P(3)’RMIX’TG(3) MAIN 1193
IF(JPERFtI.NE.3) BMASS=MMASS MAIN 1194
IF(JPERFM.EG.3) BMASS=GMASS(3) MAIN 1195
CALL WICMAC(ISTACE,BMASST(3)P(3)I1,UZ.CXUT(3),ALFA3v MAIN 1196
$RMIXPCPMIXAAA3) MAIN 1197
RHOG(3) = (1.0+G2*r1**2)**G3*RHOG(3) MAIN 1198
RHOM(3) = 1.0’((1.0-XWT(3))/RHOG(3)+XWT(3)/RHOW) MAIN 1199
RH0A(3) = (l.0+2***2)**G3*RHOG(3) MAIN 1200
TB(3) = WICBPT(TG(3)#P(3)) MAIN 1201
IF(IPRINT.EQ.2) WRITE(69624) WWMASS(3)PXWW(3)PDDAUE(M),UMASS(3), MAIN 1202
$UMASS(3)tXW(3),XtJ(3),WS(3),DAUE(N) MAIN 1203
624 FORMAT(H ,8(F12.5,lX)) MAIN 1204
IF(IPRINT.EQ.2) WRITE(69625) RHOA(3),RHOtI(3),RHOG(3),DMDTAl,DMD MAIN 1205
TA2,PW2,TW(3),TC(3) MAIN 1206
625 FORMAT(H ,#8(F12.5,lX)) MAIN 1207
DELTGW=DELTG1 MAIN 1208
DELTDW=DELTWI MAIN 1209
DELTCH=-DELTG2-DELTG3 MAIN 1210
DELP=P(3)-P(l) MAIM 1212
GAMMAO=GAMMA MAIN 1213
TB(3) = WICBPT(TG(3),P(3)) MAIN 1214
C +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C OUTPUT(STAGE PERFORMANCE) C
C C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
IF(IUNIT.NE.2) GO TO 853 MAIN 1217
W-MASS(I)=WMASS( 1)*CFM MAIN 1218
W.JWMASS(3)=W(iQSS( 3)*CFM MAIN 1219
I-TMASS( 1)=WTMASS( I)*CFM MAIN 1220
UTMASS (3) =WTMASS (3) *CFM MAIN 1221
AtASS=AMASS*CFM MAIN 1222
CHMASS=CHMASS*CF1 MAIN 1223
UMASS( I)UVMASS( I)*CFM MAIN 1224
UMASS( 3)=UMASS(3 )*CFM MAIN 1225
GMASS(1)=GtiASS(l)*CFM MAIN 1226
CtIASS(3)=CtiASS(3)*CFM MAIN 1227
TMASS( 1)=TMASS( I)*CFM MAIN 1228
TMASS(3)=TMASS(3)*CFM MAIN 1229
RHOA(1 )=RHOA( I )CFD MAIN 1230
RHOA(2)=RHOA(2)*CFD MAIN 1231
RHOA(3)=RHOA(3)*CFD MAIN 1232
RHOM(1 )=RHOM( 1)*CFD MAIN 1233
RHOM(2)=RHOM(2)*CFD MAIN 1234
RHOM(3)=RHOM(3)*CFD MAIN 1235
RHO(1)=RHO(1)*CFD MAIN 1236
RHO(2)=RHO(2)*CFD MAIN 1237
RHO(3)=RHO(3)*CFD MAIN 1238
RHOM(1)=RHOM(1)*CFD MAIN 1239
RHOM(2)=RHOM(2)*CFD MAIN 1240
RHOM(3)=RHOM(3)*CFD MAIN 1241
RHO(1)=RHO(1)*CFD MAIN 1242
RHO(2)=RHO(2)*CFD MAIN 1243
RHO(3)=RHO(3)*CFD MAIN 1244
RHO(3)=RHO(3)*CFD MAIN 1245
TG(1) =TG(1)*CFT MAIN 1246
TG(2) =TG(2)*CFT MAIN 1247
TG(3) =TG(3)*CFT MAIN 1248
TA1(1)=TA1(1)*CFT MAIN 1249
TA1(2)=TA1(2)*CFT MAIN 1250
TA1(3)=TA1(3)*CFT MAIN 1251
T41(1)=T41(1)*CFT MAIN 1252
T41(2)=T41(2)*CFT MAIN 1253
T41(3)=T41(3)*CFT MAIN 1254
P(1)=P(1)*CFP MAIN 1255
P(2)=P(2)*CFP MAIN 1256
P(3)=P(3)*CFP MAIN 1257
TB(1)=TB(1)*CFT MAIN 1258
TB(2)=TB(2)*CFT MAIN 1259
TB(3)=TB(3)*CFT MAIN 1260
TDEH(1)=TDEH(1)*CFT MAIN 1260
4073 FORMAT(1H$I_1$, 1X, $\cdots$, 1X, 1X)
4071 FORMAT(1H$I_2$, 1X, $\cdots$, 1X, 1X)
4070 FORMAT(1H$I_3$, 1X, $\cdots$, 1X, 1X)
4069 FORMAT(1H$I_4$, 1X, $\cdots$, 1X, 1X)

WRITE ($G, \cdot 4025$) CHMASS.
WRITE ($G, \cdot 4071$) XMETAN(2), XMETAN(3)
WRITE ($G, \cdot 4080$) WMASS(1), WMASS(2), WMASS(3)
WRITE ($G, \cdot 5010$) XMASS(1), XMASS(2), XMASS(3)
WRITE ($G, \cdot 6005$) RHOA, RHO(1), RHO(2), RHO(3)
WRITE ($G, \cdot 7000$) TF(1), TF(2), TF(3)
WRITE ($G, \cdot 8005$) TDEW(1), TDEW(2), TDEW(3)
WRITE ($G, \cdot 9000$) PRATIO, TRATIO, ETA(1), ETA(2), ETA(3)
WRITE ($G, \cdot 9015$) FRACTION(1), FRACTION(2), FRACTION(3)

4027 FORMAT(1H$I_5$, 1X, $\cdots$, 1X, 1X)
WRITE ($G, \cdot 4027$) CHMASS.
WRITE ($G, \cdot 4071$) XMETAN(2), XMETAN(3)
WRITE ($G, \cdot 5010$) XMASS(1), XMASS(2), XMASS(3)
WRITE ($G, \cdot 6005$) RHOA, RHO(1), RHO(2), RHO(3)
WRITE ($G, \cdot 7000$) TF(1), TF(2), TF(3)
WRITE ($G, \cdot 8005$) TDEW(1), TDEW(2), TDEW(3)
WRITE ($G, \cdot 9000$) PRATIO, TRATIO, ETA(1), ETA(2), ETA(3)
WRITE ($G, \cdot 9015$) FRACTION(1), FRACTION(2), FRACTION(3)

4026 FORMAT(1H$I_6$, 1X, $\cdots$, 1X, 1X)
WRITE ($G, \cdot 4026$) CHMASS.
WRITE ($G, \cdot 4071$) XMETAN(2), XMETAN(3)
WRITE ($G, \cdot 5010$) XMASS(1), XMASS(2), XMASS(3)
WRITE ($G, \cdot 6005$) RHOA, RHO(1), RHO(2), RHO(3)
WRITE ($G, \cdot 7000$) TF(1), TF(2), TF(3)
WRITE ($G, \cdot 8005$) TDEW(1), TDEW(2), TDEW(3)
WRITE ($G, \cdot 9000$) PRATIO, TRATIO, ETA(1), ETA(2), ETA(3)
WRITE ($G, \cdot 9015$) FRACTION(1), FRACTION(2), FRACTION(3)

4025 FORMAT(1H$I_7$, 1X, $\cdots$, 1X, 1X)
WRITE ($G, \cdot 4025$) CHMASS.
WRITE ($G, \cdot 4071$) XMETAN(2), XMETAN(3)
WRITE ($G, \cdot 5010$) XMASS(1), XMASS(2), XMASS(3)
WRITE ($G, \cdot 6005$) RHOA, RHO(1), RHO(2), RHO(3)
WRITE ($G, \cdot 7000$) TF(1), TF(2), TF(3)
WRITE ($G, \cdot 8005$) TDEW(1), TDEW(2), TDEW(3)
WRITE ($G, \cdot 9000$) PRATIO, TRATIO, ETA(1), ETA(2), ETA(3)
WRITE ($G, \cdot 9015$) FRACTION(1), FRACTION(2), FRACTION(3)

4024 FORMAT(1H$I_8$, 1X, $\cdots$, 1X, 1X)
WRITE ($G, \cdot 4024$) CHMASS.
WRITE ($G, \cdot 4071$) XMETAN(2), XMETAN(3)
WRITE ($G, \cdot 5010$) XMASS(1), XMASS(2), XMASS(3)
WRITE ($G, \cdot 6005$) RHOA, RHO(1), RHO(2), RHO(3)
WRITE ($G, \cdot 7000$) TF(1), TF(2), TF(3)
WRITE ($G, \cdot 8005$) TDEW(1), TDEW(2), TDEW(3)
WRITE ($G, \cdot 9000$) PRATIO, TRATIO, ETA(1), ETA(2), ETA(3)
WRITE ($G, \cdot 9015$) FRACTION(1), FRACTION(2), FRACTION(3)

4023 FORMAT(1H$I_9$, 1X, $\cdots$, 1X, 1X)
WRITE ($G, \cdot 4023$) CHMASS.
WRITE ($G, \cdot 4071$) XMETAN(2), XMETAN(3)
WRITE ($G, \cdot 5010$) XMASS(1), XMASS(2), XMASS(3)
WRITE ($G, \cdot 6005$) RHOA, RHO(1), RHO(2), RHO(3)
WRITE ($G, \cdot 7000$) TF(1), TF(2), TF(3)
WRITE ($G, \cdot 8005$) TDEW(1), TDEW(2), TDEW(3)
WRITE ($G, \cdot 9000$) PRATIO, TRATIO, ETA(1), ETA(2), ETA(3)
WRITE ($G, \cdot 9015$) FRACTION(1), FRACTION(2), FRACTION(3)

4022 FORMAT(1H$I_{10}$, 1X, $\cdots$, 1X, 1X)
WRITE ($G, \cdot 4022$) CHMASS.
WRITE ($G, \cdot 4071$) XMETAN(2), XMETAN(3)
WRITE ($G, \cdot 5010$) XMASS(1), XMASS(2), XMASS(3)
WRITE ($G, \cdot 6005$) RHOA, RHO(1), RHO(2), RHO(3)
WRITE ($G, \cdot 7000$) TF(1), TF(2), TF(3)
WRITE ($G, \cdot 8005$) TDEW(1), TDEW(2), TDEW(3)
WRITE ($G, \cdot 9000$) PRATIO, TRATIO, ETA(1), ETA(2), ETA(3)
WRITE ($G, \cdot 9015$) FRACTION(1), FRACTION(2), FRACTION(3)

4021 FORMAT(1H$I_{11}$, 1X, $\cdots$, 1X, 1X)
WRITE ($G, \cdot 4021$) CHMASS.
WRITE ($G, \cdot 4071$) XMETAN(2), XMETAN(3)
WRITE ($G, \cdot 5010$) XMASS(1), XMASS(2), XMASS(3)
WRITE ($G, \cdot 6005$) RHOA, RHO(1), RHO(2), RHO(3)
WRITE ($G, \cdot 7000$) TF(1), TF(2), TF(3)
WRITE ($G, \cdot 8005$) TDEW(1), TDEW(2), TDEW(3)
WRITE ($G, \cdot 9000$) PRATIO, TRATIO, ETA(1), ETA(2), ETA(3)
WRITE ($G, \cdot 9015$) FRACTION(1), FRACTION(2), FRACTION(3)

4020 FORMAT(1H$I_{12}$, 1X, $\cdots$, 1X, 1X)
WRITE ($G, \cdot 4020$) CHMASS.
WRITE ($G, \cdot 4071$) XMETAN(2), XMETAN(3)
WRITE ($G, \cdot 5010$) XMASS(1), XMASS(2), XMASS(3)
WRITE ($G, \cdot 6005$) RHOA, RHO(1), RHO(2), RHO(3)
WRITE ($G, \cdot 7000$) TF(1), TF(2), TF(3)
WRITE ($G, \cdot 8005$) TDEW(1), TDEW(2), TDEW(3)
WRITE ($G, \cdot 9000$) PRATIO, TRATIO, ETA(1), ETA(2), ETA(3)
WRITE ($G, \cdot 9015$) FRACTION(1), FRACTION(2), FRACTION(3)
WRITE (6,4140) TW(1),TW(2),TW(3)
WRITE (6,415) P(1),P(2),P(3)
WRITE (6,416) TB(1),TB(2),TB(3)
WRITE (6,422) TDEW(1),TDEW(2),TDEW(3)

IF (UNIT,NE,2) U TO 654

854 CONTINUE
C *********** CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC C
C BOILING C
C C
C C

460 IF (TW(3).LT.TB(3)) GO TO 450

450 XEUAPQX(3)
TLJ(3) = 0.0
TG(3) = (TG(3) - XH(3)) / (1.0 - XH(3)) * HV/CPG
XH(3) = 0.0
XU(3) = XU(3) + XEUAPD

452 WMASS(3) = X(3) * MMASS
UI1ASS(3) = XU(3) * iIMASS
GMMASS(3) = UMASS(3) + AMASS

IF (IPRINT.EQ.2) WRITE(69453)

453 FORMAT(1H0, #BOILINGO)

IF (IPRINT.EQ.2) WRITE(69454) HUXEUAPOT(3), TG(3), XW3, XU(3)

454 FORMAT(1H0, 10(F10.5,2X))

CONTINUE

AMASS = AMASS * ( I.* + XG1BLD( ISTAGE) )
CHMASS = CHMASS * ( 1.*0 + XG3BLD( ISTAGE) )
UMASS(3) = UMASS(3) * ( 1.0 + -XG2BLD(ISTAGE) )
W.MASS(3) = WMASS(3) * ( 1. + XWBLD(ISTAGE) )
LWMASS(3) = WWIASS(3) * ( 1.0 + XWI4BLD(ISTAGE) )
WTMASS(3) = WIASS(3) + WWIMASS(3)
MMASS = AMASS + CHMASS + UMASS(3) + WTMASS(3)
TMASS(3) = MMASS
CMASS(3) = TMASS(3) - WTMASS(3)
XW(3) = WMASS(3) / IIASS
X14W( 3) = I4WMASS(3) / MMASS
X1WT(3) = WTMASS(3) / MMASS
XV(3) = Uf1ASS(3) /iiASS
XA=AMASS/MIASS
XCH4=CHMASS/MMASS
XG=XA+"(J(3)+XCH4
XAIR(3) = XA
XMETANI(3) = XCH4
XGAS(3) = XG

C++..................................4444+++4+......+++++++4+H+

902 OUALPR=P(3)/P01
OUALTR=TC(3) /OTOIG
CAMMAV=(GAMMAI+GAMMAO)/2.0
G4=(GAMMAU-1.0)/GAMMAU
OUALEF=(OtJALPR.*G4-1.0)/(OUALTR-1.0)
OBELTG=TG( 3)-OTOIG
ODELTW=0.0
DELTUIJ=0.0
DELM=0.0
DELMWT=0.0
DELMG=0.0
IF(XDI1,CT.0.0) ODELTW=TW(3)-OTOID
IF(XDDIN.CT.0.0) DELTLI=TIJI.(3)-aTOID
DELMT = (MMASS-TLMO ) TLMO
IF(WTMO.GT.0.0) DELMWT=(WTMASS(3)-WTMD)/WTMO
DELMG= ( MASS( 3) -GMO )/GMO

C .............................
IF(IUNIT.NE.2) GO TO 855
TOG=TOG*CFT
PO=PO*CFP
CMASS=CMASS*CFM
CCMSS=CCMSS*CFM
CMASS2=C.CASS2*CFM
C2MASS=C2MASS*CFM
ODELTG=ODELTG*CFT

855 CONTINUE
WRITE(6,421)
421 FORMAT(5X ********** OVERALL PERFORMANCE **********)
WRITE(6,422) FAID
422 FORMAT(1H0, 5X, "INITIAL FLOW COEFFICIENT=", F7.5)
WRITE(6,423) CFM, CFN
423 FORMAT(1H0, 5X, "#INITIAL FLOW COEFFICIENT�", F7.5)
WRITE(6,424) XDIN, XDDIN, XHTD, XRHUM, XCH4IN
424 FORMAT(1H0, 5X, "#INITIAL WATER CONTENT(SMALL DROplet)=", FS.3)
WRITE(6,425) CV.T
425 FORMAT(1H0, 5X, "#INITIAL WATER CONTENT(TOTAL)=", FS.3)
WRITE(6,426) CFM
426 FORMAT(1H0, 5X, "#INITIAL RELATIVE HUMIDITY=", FS.3)
WRITE(6,427) CFM
427 FORMAT(1H0, 5X, "#INITIAL METHANE CONTENT=", FS.3)
WRITE(6,428) TOG
428 FORMAT(1H0, 5X, "#COMPRESSOR INLET TOTAL TEMPERATURE=", F8.2)

TOG=TOG/CFT
PO=PO*CFP
CMASS=CMASS*CFM
CCMASS=CCMASS*CFM
CMASS2=CMASS2*CFM
C2MASS=C2MASS*CFM
ODELTG=ODELTG*CFT

856 CONTINUE
GO TO 901
998 STOP
END
COMMON RRHUB(6), RC(6), RBLADE(6), STAGER(6)
COMMON SRHUB(7), SC(7), SBLADE(7), STAGES(7)
COMMON SIGMR(6), BET1SR(6), BET2SR(6), ADEUSR(6)
COMMON SIGPS7, BETISS(7), BET2SS(7), ADEJS(7)
COMMON UTPG6, UTP6, UTP6D, UOU6, UNEAN6, UHUB6, UG6, FAI
COMMON AREA6, AREAS7, UU26, UU26D, UHUB6, UG6, FAI
COMMON ICENT16, ICENT17, P1306, P1307, ETA
COMMON DMSM, AREAS7, UU27, UU27D, UHUB7, UG7, FAI
COMMON DSMA, AREA7, AAREAS7, PRI2D6, PRI3D7, ETA
COMMON NS, NS1, RT(6), RM(6), RH(6), ST(6), SM(6), SH(6)
COMMON DSMA, AREA7, AAREAS7, PRI2D6, PRI3D7, ETA
COMMON BET1MR(6), BET2MR(6), DETIMS7, PBET2MS7, PRADI16
DIMENSION RHO1(3), PETAA8

CPIJ=1.0
RH0W=62.3
CALL WICPRP(XA, XU1, XCH4, TG1, RMIX, GAMMA1, G1, G2, G3)
RHOG1=P1/RMIX/TG1
BMASS=MMASS
CALL ICMAC(ISTAGE, BMASS, TG1, P1, NUZC, XUT1, ALFA1)

$RMIX=CPMIXAREA(ISTAGE)

ASPEED=C
RHOG1=(1.0+G2*MM**2)**G3*RHOG1
RHOK1=1.0*((1.0-XIJT1)*RHOG1+XUTC1)*RHOG1
UZ=BMASS/RHOK1/AREA1 ISTAGE
UZ2=UZ
FAI=UZ/UTPG1 ISTAGE
IF(IPRINT.EQ.2) WRITE(6, 602) ISTAGE, UZ, UZ2, FAI, U1, U3

602 FORMAT(1HI1, 1X, "ROTHER INLET ISTAGE=" I2)
XC=XA+XJ1+XCH4
IF(IPRINT.EQ.2) WRITE(6,605) XC, UZ, UZ2, FAI, U1, U3

605 FORMAT(1HI1, 6(F12.5, 1X))

C VELOCITY TRIANGLE
CALL WICUT(ISTAGE, ASPEED, ALFA1, UZ, U1, U51, WS1, ETA1, ETA2,
$U25, U2, ALFA2, U3, AK1, AK3)
DELHS1=WS1-WS2
IF(IPRINT.EQ.2) WRITE(6, 610) DELHS1, WS1, WS2, ALFA1, ETA1, ETA2

610 FORMAT(1H0, 6(F12.5, 1X))

C PERFORMANCE CURVE
CALL WISCNT(ALFA1, ETA1, ETA2, ISTAGE)
ETA1=ETA1
IF(ETA1.GT.1.0) ETA1=1.0
IF(IPRINT.EQ.2) WRITE(6, 203) ISTAGE, ETA1, ETA2, P1, PRATIO

203 FORMAT(1H0, 6(F12.5, 1X))

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```plaintext
TG(3)=TG(2)
TW(3)=TW(2)
IF(IPRINT.EQ.2) WRITE(6,603)
603 FORMAT(1HO,IX,PERFORMANCE CURVE)
IF(IPRINT.EQ.2) WRITE(6,604) FAI,SAI,ETA,TAU,DELT,PRATID,P(3),
$DELHIN
604 FORMAT(1H0,F12.5,1X)
IF(IPRINT.EQ.2) WRITE(6,650) DELT.DELJI1.DELHG.DELH~hDELTC.DELTU
650 FORMAT(1H0,F12.5,1X)
RETURN
*END
SUBROUTINE LJICSCC(FAI,SAI,ETA,TAU,ISTAGE)
A1=26.456
B1=-365.48033
C1=2161.46222
D1=-6670.16668
E1=11405.5557
F1=-10280.16668
A2=-120.02
B2=1599.02
C2=-8730.12223
D2=-3922.22228
E2=-63806.66696
F2=-17333.33341
C2=-11555.55557
A3=-0.34
B3=0.226
GO TO 200
11 A1=26.456
B1=-365.48033
C1=2161.46222
D1=-6670.16668
E1=11405.5557
F1=-10280.16668
A2=-120.02
B2=1599.02
C2=-8730.12223
D2=-3922.22228
E2=-63806.66696
F2=-17333.33341
C2=-11555.55557
A3=-0.34
B3=0.226
GO TO 200
12 A1=4.265
B1=-65.44567
C1=-332.95689
D1=-907.0
E1=-1375.55556
F1=-1093.33334
A2=-116.32
B2=-1354.73334
C2=6515.80003
D2=-16503.33341
E2=23266.66677
F2=-17333.33341
C2=5333.33336
A3=0.055
B3=0.095
GO TO 200
13 A1=154.07500
B1=-1761.37834
C1=-8374.33337
D1=-21034.16676
E1=-28450.00013
F1=-21800.00010
C1=-8666.66670
D2=-492.54
B2=-5539.88003
C2=-25815.46301
D2=63806.66696
```

209
IF(IPRINT.EQ.0) WRITE(6,191) AINC,AINCR(ISTAGE),ADEVIR.

191 FORMAT(1H0,1X,4(F7.3,2X))

OMEGA1=OMEGAN
BETA2=BET2
BETA2R=BETA2*PAI/180.0
W2=U2/COS(BETA2R)
UG=(U1+U2)/2.0
OMEGA2=0.0
IF(XH(1).GT.0.0)
$CALL WICSDL(RC(ISTAGE),SIGUR(ISTAGE),BETA1,BETA2,UG,RHOG(1),
$UMA,AA1,UZ,IPRINT,OMEGA2)
OMEGA2=OMEGAP
DELP2=OMEGA2*0.5*RHOG(1)/GC*(UG**2)
OMEGA3=0.0
DELP3=0.0
BETA2R = BETA2 * PAI / 180.0

200 U2AS=U2
U2 = U2 * TAN ( BETA2R )
USE = UUE(ISTAGE) - W2
IF(UUE.LT.0.0) GO TO 999
TTT=U2/U2
ALFA2 = ALFA2 * 180.0 / PAI
TTT = U2 ** 2 + W2 ** 2
U2 = SORT ( TTTT )
TTTT = U2 ** 2 + U2 ** 2
U2 = SORT ( TTTTT )
DELH=4*KDONE*(UUE(ISTAGE)+U2-U(ISTAGE)+U1)/GC*AJ
XG=1.0-XHT(1)
CALL WICIR(ISTAGE,RRTIP(ISTAGE),X4(1),X4,UG,RHOG(1),BETA1,W1,W11,
$W3,U2)
AMHIPR=W2
IF(AMHIPR.GT.WIAS) AMHIPR=MAS
PREB=0.0
AIREBR=AMHIPR*PREB/100.0
AMRAK=AMHIPR*(1.0-PREB/100.0)
AMXIR=WMAS-AMIMPR
XHDIR=AMXIR/MASS
XAREBR=AMXIR/MASS
XWAKR=AMRAK/MASS
XH1=0.0
XH2=0.0
XH3=0.0
IF(WMAS.GT.0.0) XH1=AMXIR/MASS
IF(WMAS.GT.0.0) XH2=AMRAK/MASS
IF(WMAS.GT.0.0) XH3=AMAREB/MASS
DELG=DELH/CPHXI
DELTH=DELH/CPH
DELTHW=DELH/CPH
DELTH3=0.0
DELTH4=XH1+DELTH1+XH2+DELTH2+XH3+DELTH3
TH(2)=TH(1)+DELTH
TG(2)=TG(1)+DELG
TS2=TS(2)-U2**2/(2.0*CPHIX*GC*AJ)
AG2=GMMAK*RUMIX*TS2*GC**0.5
ASPEED=WICASD(XJ(1),RHOG(1),AG2)
AMAC2=W2/ASPEED
AMACH2=W2/ASPEED
PP1=GMMAK*RUMIX*TREL1*GC
PP2=UUE(ISTAGE)/U(ISTAGE)**2-1.0
PP3=1.0+G2*U(ISTAGE)**2/PP1*PP2
PP=P*PP1*PP2
PRREL=PP-(OMEGA1+OMEGA2+OMEGA3)*(1.0-PS1/PREL1)
PRI2=(TG(2)/TG(1))**1.0*PRREL/PP
P(2)=PRI2*P(1)
PS2=(1.0+G2*AMAC2**2)**(-1.0)*P(2)
RHOG2=PS2/RUMIX/TS2
RHOG2=RHOG2

212
RHM2=1.0/(XG/RHOG2+XWT(1)/RHOU) WICSPB 150
UZ=NMASS/RHOM2/AAA2 WICSPB 151
U2=UZ WICSPB 152
EPS=1.0E-4 WICSPB 153
IF(JJ.EQ.2) GO TO 201 WICSPB 154
IF(JJ.GT.2) GO TO 202 WICSPB 155
X1=UZAS WICSPB 156
Y1=UZ2 WICSPB 157
UZ=UZ2+JJ WICSPB 158
JJ=JJ+1 WICSPB 159
GO TO 200 WICSPB 160
201 X2=UZAS WICSPB 161
Y2=UZ2 WICSPB 162
UZ=NMINEW(X1,Y1,X2,Y2) WICSPB 163
203 FORMAT(1H1,IX,11,2X,#UZ2#,F10.5) WICSPB 164
JJ=JJ+1 WICSPB 165
IF(UZ.LT.0.0.OR.UZ.GT.ASPEED) GO TO 999 WICSPB 166
GO TO 200 WICSPB 167
202 IF(ABS(UZAS-UZ2)/UZAS),LT,EPS) GO TO 300 WICSPB 168
X1=X2 WICSPB 169
Y1=Y2 WICSPB 170
X2=UZAS WICSPB 171
Y2=UZ2 WICSPB 172
UZ=NMINEW(X1,Y1,X2,Y2) WICSPB 173
204 FORMAT(1H1,IX,11,2X,#UZ2#,F10.5) WICSPB 174
JJ=JJ+1 WICSPB 175
IF(UZ.LT.0.0.OR.UZ.GT.ASPEED) GO TO 999 WICSPB 176
IF(JJ.EQ.20) GO TO 300 WICSPB 177
GO TO 200 WICSPB 178
300 UZ2CL=UZ WICSPB 179
II=JJ+1 WICSPB 180
GO TO 2000 WICSPB 181
2010 X2=UZAS WICSPB 182
Y2=UZ2 WICSPB 183
UZ=NMINEW(X1,Y1,X2,Y2) WICSPB 184
2030 FORMAT(1H1,IX,11,2X,#UZ2#,F10.5) WICSPB 185
JJ=JJ+1 WICSPB 186
GO TO 2000 WICSPB 187
2020 IF(ABS(UZAS-UZ2)/UZAS),LT,EPS) GO TO 300 WICSPB 188
X1=XX2 WICSPB 189
Y1=YY2 WICSPB 190
XX2=UZ2CL WICSPB 191
YY2=UZ2CL WICSPB 192
UZ=NMINEW(X1,Y1,XX2,YY2) WICSPB 193
2040 FORMAT(1H1,IX,11,2X,#UZ2#,F10.5) WICSPB 194
JJ=JJ+1 WICSPB 195
GO TO 2000 WICSPB 196
2030 UZ=UZ2CL WICSPB 197
JJ=JJ+1 WICSPB 198
GO TO 200 WICSPB 199
3000 U2=UZ2CL WICSPB 200
FA=UZ2CL/UTPC(ISTAGE) WICSPB 201
P(2)=(1.0+G2*AAM2+G2)*G1+P2 WICSPB 202
JJ=JJ+1 WICSPB 203
3001 C=HICCL(OMCS(ISTAGE),SIGMS(ISTAGE),BETHSS(ISTAGE), ADEUSS(ISTAGE),AMAC,ALAF2,DEDS, $DEDN,SITACS,SITACN,BET2H,OMEGN,FM22(ISTAGE),IDESIN,A1K1,A2K2,A3K3, $U22,UZAS,0.0,RAD2(ISTAGE),RAD1(ISTAGE+1)) WICSPB 204
ASPEED=ASPEED WICSPB 205
DEDS=DEDDS WICSPB 206
SITACS=SITACN WICSPB 207
AICNS=ALAF2-BETHSS(ISTAGE) WICSPB 208
ADEUSS=BET2H-BET2HSS(ISTAGE) WICSPB 209
213
IF(IPRINT.EQ.2) WRITE(6,302) AINCIS, AINCSS(ISTAGE), ADEVIS.

302 FORMAT(1X,1X,'4(F7.3,2X))

$ADEUSS(ISTAGE)

OMEGA4=OMEGAN
ALFA4=BETA4
ALFA3=ALFA3*PAI/180.0
U3=U2/COS(ALFA3R)
UG=(U2+U3)/2.0
OMEGA=0.0

CALL WICSDL(SC(ISTAGE),SICUMS(ISTAGE),ALFA2,ALFA3,UCRHOG(2),
$MAS, AAR2, UZ, IPRINT, OMEGAP)

IF(IPRIT.EQ.2) WRITE(6,3030) JJJJ, UZ

3030 FORMAT(1H9,1X,'4(F7.3,2X))

PRINT, OMEGAP

DEL5=OMEGAS*0.5*RHOG(2)/GC(U2**2)
DEL6=0.0
OMEGA6=0.0
PRE3=1.0-(OMEGA4+OMEGAS+OMEGAP)*(1.0-P2/P(2))
PRE3=(TG(2)/TG(1))*G1
PRE3=(TG(2)/TG(1))*G1*PRREL*PR23/PP
PR3=PR23*P(3)/P(1)
TG(3)=TG(2)
TS3=T(3)-U3**2/(2.0*CPMIX*CAJ)
AG3=(CA*MA*RMIX*TS3*GC)**5
ASPEED=JICASD(XJT(1),RHOG(2),AG3)
ASPEED=ASPEED
AMAC3=U3/ASPEED
PS3=1.0*G2/AMAC3**2*(-C1)*P(3)
RHOG3=PS3/RHOG(2)*AMAC3
RHOG3=1.0/(XG/RHOG3*XJT(1)/RHOJ)
U2=BRASS/RHOM3/AAAR3
U23CL=UZ

IF(JJJJ.EQ.2) GO TO 3010
IF(JJJJ.GT.2) GO TO 3020

XXX1=UZ3AS
YYY1=UZ3CL
JJJJ=JJJJ+1
GO TO 3001

3010 XXX2=UZ3AS
YYY2=UZ3CL
UZ=HICNEU(XXX1,YYY1,XXX2,YYY2)
IF(IPRINT.EQ.2) WRITE(6,3030) JJJJ, UZ

3030 FORMAT(1X,1X,'4(F7.3,2X))

YYY2=UZ3CL
UZ=HICNEU(XXX1,YYY1,XXX2,YYY2)
IF(IPRINT.EQ.2) WRITE(6,3030) JJJJ, UZ

3020 IF(RABS((UZ3AS-UZ3CL)/UZ3AS).LT.EPS) GO TO 4000

XXX1=XXX2
YYY1=YYY2
XXX2=UZ3AS
YYY2=UZ3CL
UZ=HICNEU(XXX1,YYY1,XXX2,YYY2)
IF(IPRINT.EQ.2) WRITE(6,3040) JJJJ, UZ

3040 FORMAT(1X,1X,'4(F7.3,2X))

YYY2=UZ3CL
UZ=HICNEU(XXX1,YYY1,XXX2,YYY2)
IF(IPRINT.EQ.2) WRITE(6,3040) JJJJ, UZ

4000 UZ=UZ3CL
FAI3=UZ3-UTIPG(ISTAGE+1)
TU(3)=TU(2)

OMEGT=OMEGA1+OMEGA2+OMEGA3
OMEGT5=OMEGA4+OMEGAS+OMEGAP
POMEGT=OMEGA1/OMEGT**100.0
POMEGAS=OMEGA2/OMEGT**100.0
POMEG2=OMEGA3/OMEGT**100.0
POMEG4=OMEGA4/OMEGAS**100.0
POMEG5=OMEGAS/OMEGT**100.0
POMEG6=OMEGAP/OMEGAS**100.0
POMEGE=POMEG2*POMEG3*POMEG4*POMEG5*POMEG6

PRATIO=P(3)/P(1)
TRATIO=TG(3)/TG(1)
CALL WICPRP(XA, XU(3), XCH4, TG(3), RMIX, CPMIX, GAMMA, C1, C2, C3)

214
GAMMA2 = GAMMA
GAMMAU = (GAMMA1 + GAMMA2) / 2.0
C4 = (GAMMAU - 1.0) / GAMMAU
ETAR(ISTAGE) = (PRATIO**C4 - 1.0) / (TRATIO - 1.0)
IF (UNIT,NE,2) GO TO 857
UTIPG(ISTAGE) = UTIPG(ISTAGE) * CFP
P(1) = P(1) * CFP
P(2) = P(2) * CFP
P(3) = P(3) * CFP
PS1 = PS1 * CFP
PS2 = PS2 * CFP
PS3 = PS3 * CFP
TG(1) = TG(1) * CFT
TG(2) = TG(2) * CFT
TG(3) = TG(3) * CFT
TS1 = TS1 * CFT
TS2 = TS2 * CFT
TS3 = TS3 * CFT
RHOG(1) = RHOG(1) * CFD
RHOG(2) = RHOG(2) * CFD
RHOG(3) = RHOG(3) * CFD
RHOM(1) = RHOM(1) * CFD
RHOM(2) = RHOM(2) * CFD
RHOM(3) = RHOM(3) * CFD
U21 = U21 * CFU
U22 = U22 * CFU
U23 = U23 * CFU
U1 = U1 * CFU
U2 = U2 * CFU
U3 = U3 * CFU
W1 = W1 * CFU
W2 = W2 * CFU
W3 = W3 * CFU
ASPEED1 = ASPEED1 * CFU
ASPEED2 = ASPEED2 * CFU
ASPEED3 = ASPEED3 * CFU
AAA1 = AAA1 * CFA
AAA2 = AAA2 * CFA
AAA3 = AAA3 * CFA
857 CONTINUE
WRITE(6,404) FAID,ISTAGE
WRITE(6,405) P(1),P(2),P(3)
WRITE(6,406) TG(1),TG(2),TG(3)
857
408 FORMAT(IH,1X,'TOTAL TEMPERATURE(GAS)#,3X,3(F10.4,5X))
WRITE(6,409) TS1,TS2,TS3
409 FORMAT(1H,1X,'STATIC TEMPERATURE(GAS)#,1X,3(F10.4,5X))
WRITE(6,410) RHOM1,RHOM2,RHOM3
410 FORMAT(1H,1X,'STATIC DENSITY(GAS)#,5X,3(F10.4,5X))
WRITE(6,411) RHOM1,RHOM2,RHOM3
411 FORMAT(1H,1X,'STATIC DENSITY(MIXTURE)#,1X,3(F10.4,5X))
WRITE(6,412) UZ1,UZ2,UZ3
412 FORMAT(1H,0X,'AXIAL VELOCITY#,1X,3(F10.4,5X))
WRITE(6,413) U1,U2,U3
413 FORMAT(1H,1X,'ABSOLUTE VELOCITY#,7X,3(F10.4,5X))
WRITE(6,414) W1,W2,W3
414 FORMAT(1H,0X,'RELATIVE VELOCITY#,7X,2(F10.4,5X))
WRITE(6,415) W1,W2,W3
415 FORMAT(1H,1X,'BLADE VELOCITY#,#1X,3(F10.4,5X))
WRITE(6,416) ASPI,ASPED2,ASPED3
416 FORMAT(1H,0X,'COMP. OF ABS. VELOCITY#,2(F10.4,5X))
WRITE(6,417) ASPI,ASPED2,ASPED3
417 FORMAT(1H,1X,'COMP. OF REL. VELOCITY#,2(F10.4,5X))
WRITE(6,418) ASPED1,ASPED2,ASPED3
418 FORMAT(1H,1X,'ACOUSTIC VELOCITY#,10X,3(F10.4,5X))
WRITE(6,419) AMAC1,AMAC2,AMAC3
419 FORMAT(1H,1X,'ABSOLUTE MACH NUMBER#,4X,3(F10.4,5X))
WRITE(6,420) AMAC1,AMAC2,AMAC3
420 FORMAT(1H,1X,'RELATIVE MACH NUMBER#,4X,2(F10.4,5X))
WRITE(6,421) FM1,FM2,FM3
421 FORMAT(1H,1X,'FLOW COEFFICIENT#,8X,3(F10.4,5X))
WRITE(6,422) AAA1,AAA2,AAA3
422 FORMAT(1H,1X,'FLOW AREA#,15X,3(F10.4,5X))
WRITE(6,423) ALFA1,ALFA2,ALFA3
423 FORMAT(1H,1X,'ABSOLUTE FLOW ANGLE#,5X,3(F10.4,5X))
WRITE(6,424) BETA1,BETA2,BETA3
424 FORMAT(1H,1X,'RELATIVE FLOW ANGLE#,5X,3(F10.4,5X))
WRITE(6,425) AR1,AR2,AR3
425 FORMAT(1H,1X,'INCIDENCE#,15X,2(F10.4,5X))
WRITE(6,426) AR1,AR2,AR3
426 FORMAT(1H,1X,'DEVIATION#,30X,2(F10.4,5X))
IF(UNIT.NE.2) GO TO 858
UTIPG(ISTAGE)=UTIPG(ISTAGE)/CFU
U1=U1/CFU
U2=U2/CFU
U3=U3/CFU
W1=W1/CFU
W2=W2/CFU
U(ISTAGE)=U(ISTAGE)/CFU
U2(ISTAGE)=U2(ISTAGE)/CFU
U(ISTAGE+1)=U(ISTAGE+1)/CFU
UT1=UT1/CFU
UT2=UT2/CFU
UT3=UT3/CFU
W(ISTAGE)=W(ISTAGE)/CFU
W2(ISTAGE)=W2(ISTAGE)/CFU
W(ISTAGE+1)=W(ISTAGE+1)/CFU
UZ1=UZ1/CFU
UZ2=UZ2/CFU
UZ3=UZ3/CFU
PS1=PS1/CFP
PS2=PS2/CFP
PS3=PS3/CFP
PS1=PS1/CFP
PS2=PS2/CFP
PS3=PS3/CFP
T1=T1/CFP
T2=T2/CFP
T3=T3/CFP
RHOC1=RHOC1/CFD
RHOC2=RHOC2/CFD
RHOC3=RHOC3/CFD
RHOD1=RHOD1/CFD
RHOD2=RHOD2/CFD
RHOD3=RHOD3/CFD
V21=V21/CFU
V22=V22/CFU
V23=V23/CFU
V1=V1/CFU
V2=V2/CFU
V3=V3/CFU
W1=W1/CFU
W2=W2/CFU
W3=W3/CFU
U(ISTAGE)=U(ISTAGE)/CFU
UU(ISTAGE)=UU(ISTAGE)/CFU
U(IISTAGE+1)=U(IISTAGE+1)/CFU
W1=W1/CFU
W2=W2/CFU
W3=W3/CFU
SUBROUTINE WICSPC

C****************************************************************************
C
C SUBROUTINE WICSPC(FAIO, ISTAGE, MMASS, ALFAI, WDONE, DAU, DELU, UMAAS, 
C SAREA, N)
C
C**************************************************************
C
COMMON TD(7), IUNIT
COMMON CFL, CF, CFP, CFT, CFD, CFM, CR3
COMMON JPERF, RHOC(3), RERUP, RERLOW
COMMON PREB, RRHUB(G), SC(G), SRHUB(7)
COMMON P(3), TC(3), XA, XV(3), XCH4, XW(3)
COMMON OMEGAS(7), OMEC(6), CAPR(6), GAPS(6)
COMMON RRHUB(G), SC(G), SRHUB(7)
COMMON SICUMR(G), BETISS(7), B2SS(7)
COMMON SIGUMS(7)
COMMON UTIPG(6), UTIP(6), UTIPD(6), UO(6), UMEAN(6)
COMMON OMEGA1, OMEGA2, OMEGA3, OMEGA4, OMEGA5, OMEGA6, OMEGA7,
COMMON OMEGAS(7)

REAL M, MMASS
COMMON TDC7), IUNIT

REAL RHOM(3), ETA(3)
DIMENSION RHOM(3), ETA(3)

IPRINT=1
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CPCWPB 555
CPCWPB 556
CPCWPB 557
CPCWPB 558
CPCWPB 559
TT = UZ **2 + WSI **2
W1 = SORT (TT)
AMACHI = W1 / ASPEED
AMACI=U1/ASPEED
TS1=TG(1)/(1.0+G2*AMACI**2)
PSI=<(TG(1)-TS1)**(-G1)*P(1)
PREL1=(1.0+G2*AMACHI**2)**G1*PSI
TRE(1)=(1.0+G2*AMACHI**2)*TS1
TG(2)=TG(1)
P(2)=P(1)
ALFAR=BI1SS(ISTAGE)
JUL=1

2000 U2AS=UZ
CALL WICGSL(OMEGR(ISTAGE),SIGUMR(ISTAGE),BET1SR(ISTAGE),BET2SR(ISTAGE),AICSR(ISTAGE),ADEVSR(ISTAGE),AMACHI,BETA1,DEGS,DEGM,$ISTAGE),AICSR(ISTAGE),ADEVSR(ISTAGE),AMACHI,BETA1,DEGS,DEGM,$ISTAGE,SKIP=BET2,OMEGE,PR1(ISTAGE),IDESIN,AK1,AK2,AK3,US1,$U2AS,U(ISTAGE),RADII(ISTAGE),RAD2(ISTAGE))

OMEA7=OMEGAE
BETAR=BET1R
BETA1R=BETA1R/PAI/180.0
BETA2R=BETA2R/PAI/180.0
BETAUE=(BETA1R+BETA2R)/2.0
TANGT=WICTAN(BETA1R)-WICTAN(BETA2R)
CSAV=CSSINE(BETAUE)
CL=2.0/SIGUMP(ISTAGE)*TANGT*CSAU

DMEA1=tlEGAl
AIrICIR=BETAI-BETIMA(ISTAGE)
ADEVIR=BET2i-BET2MR(ISTAGE)

BETA2R=BETA2*PAI/180.*0

UG=(Wl+1J2)/2.0

CALL WMIFLS(W1,W2,F71ASSR.RHOG(1),RC(ISTAGE)SUGUIR(ISTAGE),BETAI)

PRT=(0.020*SHR

OMEGAR=OMEGE *(CS1**2)/(CSAV**3)
H=RRTIP(ISTAGE)-RRHUB(ISTAGE)
SHR=RC(ISTAGE)/H*SUGUMR(ISTAGE)
CDA=0.020*SHR

BETAR=BIIPR/100.0
BETAR=BIIPR*(1.0-PREB/100.0)
BETAR=BIIPR/100.0

XUWRXR=BMREBR/MUASS
XWWWAR=BMREBR/MUASS
G=H/1/2/2.0

CALL WICRSL(SIGUMR(ISTAGE),BETAI,BETAR,RC(ISTAGE)DAV,CDAR,OMEGAR)

DELP1=OMEGA1/5.0*RHOG(1)/GC*(Wl**2)

IF(IPRIT.EQ.2) WRITE(696090)

XG=1.0-XWT(1)

CALL WICIRL(ISTAGE,RRTIP(ISTAGE),XUW(1),XG,RHOG(1),BETAI,W1,WW1,WW $2,WW)

RSTI=RADI(ISTAGE)**2-AAA1*144.0/2.0/PAI
RSTI=SORT(RSTI)
RST2.0*RADI(ISTAGE)**2-RSTI**2
RST2=SORT(RST2)
DELR=(RST2-RST1)/12.0
FMSSR=BMARK/DELR

CALL WICMFL(W1,W2,FMASSR,RHOG(1),RC(ISTAGE),SIGUMR(ISTAGE),BETAI, $BET2R,CDF.OMEGAF)

OMEGA2=OMEGA

DELP2=OMEGA2/5.0*RHOG(1)/GC*(Wl**2)

IF(IPRIT.EQ.2) WRITE(6,6091) OMEGA1,DELP1

6090 FORMAT(IH ,7(F12.5,1X))

RSTI=RADI(ISTAGE)**2-AAA1*144.0/2.0/PAI
RSTI=SORT(RSTI)
RST2.0*RADI(ISTAGE)**2-RSTI**2
RST2=SORT(RST2)
DEL=(RST2-RST1)/12.0
FMSSR=BMARK/DELR

CALL WICMFL(W1,W2,FMASSR,RHOG(1),RC(ISTAGE),SIGUMR(ISTAGE),BETAI, $BET2R,CDF.OMEGAF)

OMEGA2=OMEGA

DELP2=OMEGA2/5.0*RHOG(1)/GC*(Wl**2)

IF(IPRIT.EQ.2) WRITE(6,6091) OMEGA2,DELP2

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6091 FORMAT(1H ,1X,'#OMEGA2=##,2F10.5)
     U2=0.0
     U3=0.0
     ALFA=0.0
     ALFA3=0.0
     CALL WICSTL(ISTAGE, 1.DAU.WI.W2.DELUU2.U3,uuMASPuZNBETAI1,BTAB.
     SDRAVR, DRACRL, DRAGSL, REAVE)
     OMEGA3=OMEGRU+OZGRU
     DFL3=OMEGR3*0.5*RHOG1)/GC*(U1**2)
     IF(IPRINT.EQ.2) WRITE(6,6092) OMEG3, DFL3
6092 FORMAT(1H ,1X,'#OMEGA3=#,2F10.5)
     REAVE1=REAVE
     BETA2R = BETA2 * PAI/
     JJ=1
     U2AS=U2
     U2E=UU2(ISTAGE) - U2
     TTT=U2/U2
     ALFA2R = ATAN ( 2TTT)
     ALFA2 = ALFA2R * 180.0 / PAI
     TTTT=U2 + U2S ** 2
     U2 = SORT ( TTTT)
     UZ=KDONE(UU2(ISTAGE)+US2-U(ISTAGE)+U2)/GC/2
     call WICRIS(ISTAGE,RRTIP(ISTAGE),XW1(1),XGRHOG()BETA,I,11j1,
     WW2.
     W.W)
     AMIMPR=W.W
     IF(AMIMPR.CT.LIMAS) AMIMPR=UMAS
     PREB=50.0
     AMREB=AMIMPR*PREB/100.0
     ASWAKR=AMIMPR*(1.0-PREB/100.0)
     AMNOIR=WMAS-AMIMPR
     XW1=0.0
     XW2=0.0
     XW3=0.0
     IF(WMAS.GT.0.0) XW1=AMNOIR/WMAS
     IF(WMAS.GT.0.0) XW2=ASWAKR/WMAS
     IF(WMAS.GT.0.0) XW3=AMREB/WMAS
     DELTG=DELTG/CP1
     DELTJ2=DELTG/CP4
     DELTW3=0.0
     DELTW=XWI*DELTW1+XW2*DELTW2,XW3*DELTW3
     DETWW1=0.0
     DETWW2=0.0
     DETWW3=0.0
     DELTWW=0.0
     TW(2)=TW(1)+DELTW
     TW(2)=TW(1)+DELTW1
     TG(2)=TG(1)+DELTG
     TS2=TS2-U2**2/(2.0*CPMX*GC*2)
     AG2=AG2*RMIX*TS2/2**0.5
     ASPEED=WICASD(XWT(1),RHOG(1),AG2)
     ASPEED2=ASPEED
     AMAC2=W2/ASPEED
     AMACH2=W2/ASPEED
     PP1=PP1*RMIX*TRM1*GC
     PP1=PP1*SU2(ISTAGE)+U(ISTAGE)**2-1.0
     PP3=1.0+2*U(ISTAGE)**2/PP1+PP2
     PP=PP3**G1
     PRHEL=PP*(OMEGA7+OMEGA1+OMEGA2+OMEGA3)*(1.0-PS1/PREL1)
     PR12=(TG(2)+TG(1))*G2*PRREL/PP
     P(2)=PR12*P(1)
     PS2=(1.0+G2*AMAC2**2)**(-G1)*P(2)
     RHOG2=PS2/RMIX*TS2
     RHOM2=1.0/(XG/RHOG2+XW1(1)/RHOG1)
     UZ=BMAS/RHOG2/RHOG1
UZ2=UZ
EPS=1.0E-4
IF(JJ.EQ.2) GO TO 201
IF(JJ.GT.2) GO TO 202
X1=UZAS
Y1=UZ2
UZ=UZ2
JJ=JJ+1
IF(UZ.LT.0.0.OR.VZ.GT.ASPEED) GO TO 999
GO TO 200
201 X2=UZAS
Y2=UZ2
UZ=WICNEW(X1,Y1,X2,Y2)
IF(IPRINT.EQ.2) WRITE(6,203) JJ,UZ
203 FORMAT(1H0,IX,11,2X,UZ2=,#F10.5)
JJ=JJ+1
IF(UZ.LT.0.0.OR.UZ.GT.ASPEED) GO TO 999
GO TO 200
202 IF(ABS((UZAS-UZ2)/VZAS).LT.EPS) GO TO 300
X1=X2
Y1=Y2
X2=UZAS
Y2=UZ2
UZ=WICNEW(X1,Y1,X2,Y2)
IF(IPRINT.EQ.2) WRITE(6,204) JJ,UZ
204 FORMAT(1H0,IX,11,2X,UZ2=,#F10.5)
JJ=JJ+1
IF(UZ.LT.0.0.OR.VZ.GT.ASPEED) GO TO 999
GO TO 200
300 UZ2CL=UZ
IF(JJJ.EQ.2) GO TO 2010
IF(JJJ.GT.2) GO TO 2020
XX1=UZ2AS
YY1=UZ2CL
JJJ=JJJ+1
GO TO 2000
2010 XX2=UZ2AS
YY2=UZ2CL
UZ=WICNEW(XX1,YY1,XX2,YY2)
IF(IPRINT.EQ.2) WRITE(6,2030) JJJ,UZ
2030 FORMAT(1H0,IX,11,2X,UZ2=,#F10.5)
JJJ=JJJ+1
GO TO 2000
2020 IF(ABS((UZ2AS-UZ2CL)/UZ2AS).LT.EPS) GO TO 3000
XX1=XX2
YY1=YY2
XX2=UZ2AS
YY2=UZ2CL
UZ=WICNEW(XX1,YY1,XX2,YY2)
IF(IPRINT.EQ.2) WRITE(6,2040) JJJ,UZ
2040 FORMAT(1H0,IX,11,2X,UZ2=,#F10.5)
JJJ=JJJ+1
IF(JJJ.EQ.20) GO TO 3000
GO TO 2000
3000 UZ2=UZ2CL
FA12=UZ2/UTIPG(ISTAGE)
GO TO 200
3001 UZ3AS=UZ
CALL WICGL(OMEGS(ISTAGE),SIGNS(ISTAGE),BETISS(ISTAGE),BETISS(ISTAGE),BET2SS
X2=IAGE),AINCSS(ISTAGE),ADESSS(ISTAGE),AMACE2,ALFA2,DESS,DESII,
$SITACS,SITAGN,BETAN,OMEGAN,FNAG(ISTAGE),IDESII,AK1,AK2,AK3,UZ2,
$UZ3AS=0.0,RAD1(ISTAGE)+RAD1(ISTAGE+1))
OMEGAN=OMEGAN
ALFA3=BETAN
ALFAIR=ALFA3*PAI/180.0
ALFA2=ALFA3*PAI/180.0
ALFA3=ALFAIR+ALFA2/2.0
TANG=WICTAN(ALFAIR)-WICTAN(ALFA2)
220
CSAU = COS(ALFAAU) WICSPC 270
CS1 = COS(ALFAIR) WICSPC 271
C12 = 0.018*(C1**2) WICSPC 272
OMEGSe = COS(SIGUSS(I STAGE) + CS1**2)/(CSAU**2) WICSPC 273
H = SRTIP(I STAGE) - SHRUB(I STAGE) WICSPC 274
SHR = SCI(I STAGE) / H - SIGUR(I STAGE) WICSPC 275
CDA = 0.05*SHR WICSPC 276
OMEGAn = COS(SIGUSS(I STAGE) + CS1**2)/(CSAU**2) WICSPC 277
IF(IPRINT.EQ.2) WRITE(6,3002) WICSPC 278
$OMEg4, OMEg5, OMEgN, OMEgA, CDs, CDa WICSPC 279
3002 FORMAT(1H0.6F10.5) WICSPC 280
OMEg2 = OMEg5 WICSPC 281
OMEgA = OMEgN WICSPC 282
$BETA2, CDf, OMEgAF WICSPC 283
OMEGa = OMEgA WICSPC 284
DELPS = OMEgA**0.5*RHOG2/CC*(U2**2) WICSPC 285
IF(IPRINT.EQ.2) WRITE(6,6616) OMEgA, DELPS WICSPC 286
6616 FORMAT(1H1X,*0MEgA=0,2F10.5) WICSPC 287
$REAs, BMWAKs WICSPC 288
6617 FORMAT(1H18(F12.5,1X)) WICSPC 289
WICSTL(I STAGE, SRTIP(I STAGE), XW(2), XG, RHOG2, ALFA2, U2, U1 WICSPC 290
$U,N) BMWAKs=WWMAS WICSPC 291
BMREBS=BMRPS*PREB/100.0 WICSPC 292
BMWAKs=BMRPS*(1.0-PREB/100.0) WICSPC 293
IF(IPRINT.EQ.2) WRITE(6,6617) BMWAKs, BMREBS, BMUAKs WICSPC 294
6618 FORMAT(1H1X,*0MEgA**2,2F10.5) WICSPC 295
REAUe2=REAUe1+REAUe2*0.5 WICSPC 296
PR23=1.0*(OMEGa+OMEGa+OMEGa+OMEGa+OMEGa)*(1.0-PS2/P(2)) WICSPC 297
PR13=1.0*(TG(2)/TG(1)**G1*PRREL*PR23/F P WICSPC 298
PR13=1.0*(TG(2)/TG(1)**G1*PRREL*PR23/F P WICSPC 299
PR13=1.0*(TG(2)/TG(1)**G1*PRREL*PR23/F P WICSPC 300
P(3)=PR13*P(1) WICSPC 301
TG(3)=TG(2) WICSPC 302
TS3=TG(3)**U3**2/(2.0*CPMIX*GC*A J) WICSPC 303
AC3=CAMMA+RMMX+TS3**GC*0.5 WICSPC 304
ASPEED3=ASPEED**0.5*(XH(1)+RHOG2)**2.0) WICSPC 305
ASPEED3=ASPEED**0.5*(XH(1)+RHOG2)**2.0) WICSPC 306
AC33/(XH(1)+RHOG2)**2.0) WICSPC 307
UZ=BRASS/RHOG3/UZ43 WICSPC 308
UZ23L=UZ WICSPC 309

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IF(JJJJ.EQ.2) GO TO 3010
IF(JJJJ.GT.2) GO TO 3020
XXX1=UZ3AS
YYV1=UZ3CL
JJJJ=JJJJ+1
GO TO 3001
3010
XXX2=UZ3AS
YYV2=UZ3CL
UZ=WICSPC(XXX1,YYV1,XXX2,YYV2)
IF(IPRINT.EQ.2) WRITE(6,3030) JJJJ,UZ
3030 FORMAT(1H,1X,12,2X,#UZ3=#,F10.5)
JJJJ=JJJJ+1
GO TO 3001
3020 IF(ABS((UZ3AS-UZ3CL)/UZ3AS).LT.EPS) GO TO 4000
XXX1=XXX2
YYV1=YYV2
XXX2=UZ3AS
YYV2=UZ3CL
UZ=WICSPC(XXX1,YYV1,XXX2,YYV2)
IF(IPRINT.EQ.2) WRITE(6,3040) JJJJ,UZ
3040 FORMAT(1H,1X,12,#UZ3AS=#,F10.5)
JJJJ=JJJJ+1
IF(JJJJ.EQ.20) GO TO 4000
GO TO 3001
4000 UZ3=UZ3CL
XXA3=UZ3/UTIPG(ISTAGE+1)
TH(1)=TH(2)
TH(3)=TH(2)
OMEGT=OMEGA1+OMEGA2+OMEGA3+OMEGA7
OMEGS=OMEGA4+OMEGA5+OMEGA6+OMEGA8
POMEGI=OMEGA1/OMEGT*100.0
POMEG2=OMEGA2/OMEGT*100.0
POMEG3=OMEGA3/OMEGT*100.0
POMEG4=OMEGA4/OMEGT*100.0
POMEG5=OMEGA5/OMEGT*100.0
POMEG6=OMEGA6/OMEGT*100.0
POMEG7=OMEGA7/OMEGT*100.0
POMEG8=OMEGA8/OMEGT*100.0
PRATIO=P(3)/P(1)
TRATIO=SIGMA(3)/SIGMA(1)
CALL WICPRP(XA,XU(3),XXXX,TH(3),RMIK,CMIX,GAMMA,G1,G2,G3)
GAMMA=CMIX
GAMMA=(GAMMA1+GAMMA2)/2.0
G4=(GAMMA1-1.0)/GAMMA
ETAA(ISTAGE)=(PRATIO*G4-1.0)/(TRATIO-1.0)
IF(UNIT-N.E.2) GO TO 859
UTIPG(ISTAGE)=UTIPG(ISTAGE)*CFU
P(1)=P(1)*CFP
P(2)=P(2)*CFP
P(3)=P(3)*CFP
PS1=PS1*CFP
PS2=PS2*CFP
PS3=PS3*CFP
TG(1)=TG(1)*CFI
TG(2)=TG(2)*CFI
TG(3)=TG(3)*CFI
TS1=TS1*CFI
TS2=TS2*CFI
TS3=TS3*CFI
RHOG(1)=RHOG(1)*CFD
RHOG2=RHOG2*CFD
RHOG3=RHOG3*CFD
RHOM(1)=RHOM(1)*CFD
RHOM2=RHOM2*CFD
RHOM3=RHOM3*CFD
UZ1=UZ1*CFU
UZ2=UZ2*CFU
UZ3=UZ3*CFU
U1=U1*CFU
U2=U2*CFU
U3=U3*CFU

W1=W1*CFV

W2=W2*CFU

U(ISTAGE)=U(ISTAGE)*CFU

U(ISTAGE+1)=U(ISTAGE+1)*CFU

VSI=USI*CFU

US2=US2*CFU

WS1=WS1*CFV

WS2=WS2*CFU

ASPE1=ASPE1*CFU

ASPE2=ASPE2*CFU

ASPE3=ASPE3*CFU

AAA1=AAA1*CFV

AAA2=AAA2*CFV

AAA3=AAA3*CFV

CONTINUE

WRITE(6,404) FAI,ISTAGE

WRITE(6,405) P(1),P(2),P(3)

WRITE(6,406) P(1),P(2),P(3)

WRITE(6,407) PS1,PS2,PS3

WRITE(6,408) TG1,TG2,TG3

WRITE(6,409) TS1,TS2,TS3

WRITE(6,410) RHOD1,RHOD2,RHOD3

WRITE(6,411) RHOD1,RHOD2,RHOD3

WRITE(6,412) U1/U2/U3

WRITE(6,413) U1, U2, V3

WRITE(6,414) U1, U4

WRITE(6,415) U(U(ISTAGE),U(ISTAGE+1))

WRITE(6,416) US1,US2

WRITE(6,417) US1,US2

WRITE(6,418) US1,US2

WRITE(6,419) US1,US2

WRITE(6,420) US1,US2

WRITE(6,421) US1,US2

WRITE(6,422) AAA1,AAA2,AAA3

WRITE(6,423) AAA1,AAA2,AAA3

WRITE(6,424) AAA1,AAA2,AAA3

WRITE(6,425) AAA1,AAA2,AAA3

WRITE(6,426) AAA1,AAA2,AAA3

WRITE(6,427) AAA1,AAA2,AAA3

WRITE(6,428) AAA1,AAA2,AAA3

WRITE(6,429) AAA1,AAA2,AAA3

WRITE(6,430) AAA1,AAA2,AAA3

WRITE(6,431) AAA1,AAA2,AAA3

WRITE(6,432) AAA1,AAA2,AAA3

WRITE(6,433) AAA1,AAA2,AAA3

WRITE(6,434) AAA1,AAA2,AAA3

WRITE(6,435) AAA1,AAA2,AAA3

WRITE(6,436) AAA1,AAA2,AAA3

WRITE(6,437) AAA1,AAA2,AAA3

WRITE(6,438) AAA1,AAA2,AAA3

WRITE(6,439) AAA1,AAA2,AAA3

WRITE(6,440) AAA1,AAA2,AAA3

WRITE(6,441) AAA1,AAA2,AAA3

WRITE(6,442) AAA1,AAA2,AAA3

WRITE(6,443) AAA1,AAA2,AAA3

WRITE(6,444) AAA1,AAA2,AAA3

WRITE(6,445) AAA1,AAA2,AAA3

WRITE(6,446) AAA1,AAA2,AAA3

WRITE(6,447) AAA1,AAA2,AAA3

WRITE(6,448) AAA1,AAA2,AAA3

WRITE(6,449) AAA1,AAA2,AAA3

WRITE(6,450) AAA1,AAA2,AAA3

WRITE(6,451) AAA1,AAA2,AAA3

WRITE(6,452) AAA1,AAA2,AAA3

WRITE(6,453) AAA1,AAA2,AAA3

WRITE(6,454) AAA1,AAA2,AAA3

WRITE(6,455) AAA1,AAA2,AAA3

WRITE(6,456) AAA1,AAA2,AAA3

WRITE(6,457) AAA1,AAA2,AAA3

WRITE(6,458) AAA1,AAA2,AAA3

WRITE(6,459) AAA1,AAA2,AAA3

WRITE(6,460) AAA1,AAA2,AAA3

WRITE(6,461) AAA1,AAA2,AAA3

WRITE(6,462) AAA1,AAA2,AAA3

WRITE(6,463) AAA1,AAA2,AAA3

WRITE(6,464) AAA1,AAA2,AAA3

WRITE(6,465) AAA1,AAA2,AAA3

WRITE(6,466) AAA1,AAA2,AAA3

WRITE(6,467) AAA1,AAA2,AAA3

WRITE(6,468) AAA1,AAA2,AAA3

WRITE(6,469) AAA1,AAA2,AAA3

WRITE(6,470) AAA1,AAA2,AAA3

WRITE(6,471) AAA1,AAA2,AAA3

WRITE(6,472) AAA1,AAA2,AAA3

WRITE(6,473) AAA1,AAA2,AAA3

WRITE(6,474) AAA1,AAA2,AAA3

WRITE(6,475) AAA1,AAA2,AAA3

WRITE(6,476) AAA1,AAA2,AAA3

WRITE(6,477) AAA1,AAA2,AAA3

WRITE(6,478) AAA1,AAA2,AAA3

WRITE(6,479) AAA1,AAA2,AAA3
WRITE(6,423) ALFA1, ALFA2, ALFA3
423 FORMAT(1H0, 1X, "#ABSOLUTE FLOW ANGLE=", 5X, 3(F10.4, 5X))
WRITE(6,424) BE1, BET2
424 FORMAT(1H0, 1X, "#RELATIVE FLOW ANGLE=", 5X, 3(F10.4, 5X))
WRITE(6,425) AINC, AINCIS
425 FORMAT(1H0, 1X, "#INCIS=", 16X, 2(F10.4, 5X))
WRITE(6,426) ADEVRI, ADEVR
426 FORMAT(1H0, 1X, "#DEVIATION=", 30X, 2(F10.4, 5X))
IF(IUNIT.NE.2) GO TO 860
UTIPG(I STAGE)=UTIPG(I STAGE)/CFU
P(1)=P(1)/CFP
P(2)=P(2)/CFP
P(3)=P(3)/CFP
PS1=PS1/CFP
PS2=PS2/CFP
PS3=PS3/CFP
TG(1)=TG(1)/CFT
TG(2)=TG(2)/CFT
TG(3)=TG(3)/CFT
TS1=TS1/CFT
TS2=TS2/CFT
TS3=TS3/CFT
RHOG(1)=RHOG(1)/CFD
RHOG2=RHOG2/CFD
RHOG3=RHOG3/CFD
RHOM(1)=RHOM(1)/CFD
RHOM2=RHOM2/CFD
RHOM3=RHOM3/CFD
U21=U21/CFU
U22=U22/CFU
U23=U23/CFU
U1=U1/CFU
U2=U2/CFU
U3=U3/CFU
W1=W1/CFU
W2=W2/CFU
W3=W3/CFU
U(I STAGE)=U(I STAGE)/CFU
UU2(I STAGE)=UU2(I STAGE)/CFU
U(I STAGE+1)=U(I STAGE+1)/CFU
US1=US1/CFU
US2=US2/CFU
US3=US3/CFU
ASPED1=ASPED1/CFU
ASPED2=ASPED2/CFU
ASPED3=ASPED3/CFU
AAA1=AAA1/CFU
AAA2=AAA2/CFU
AAA3=AAA3/CFU
SUBROUTINE WICMAC
SUBROUTINE WICMAC(I STAGE, AMASSM, TOIG, PRES, R, UZ, CX, ALFA, H)
REAL R, MAI, MC1, MA2, MC2, MANEW, MCNEW
COMMON T(7), IUNIT
COMMON CFL, CFT, CF, CFM, CFU, CFA
COMMON JPERFM, RHOG(3), RERUP, RERLO, RESUP, RESLO
COMMON PRED, RRTIP(8), SRTIP(8), AAI1, AAI2, AAI3, SAREA(6), SAREAS(7)
COMMON P(3), TG(3), XA(3), XCH4, XU(3), XH(3), XTi(3), T(3), TiH(3)
COMMON QMECS(7), CMEDR(6), GAPR(6), CAPR(6)
COMMON RHRUB(6), RC(6), RBLADE(6), STAGER(6)
COMMON SRHUB(7), SC(7), SBLADE(7), STAGES(7)
COMMON SIGM(6), BETISR(6), BETESR(6), AINCSR(6), ADEVSR(6)
END
COMMON SIGUMS(7), BETASS(7), AIMCSS(7), ADEUSS(7)
COMMON UTPG(6), UTP(6), UTPD(6), UOU(6), UMEAN(6), UHUB(6), U6(6), FAI
COMMON AREA(6), AREAS(7), U2E(6), UTPS(6), UMEAN(6), UHUB(6), IPRINT
COMMON NSN1, RT(6), RM(6), ST(6), SM(6), SM(6)
COMMON DSASSW, AREA(7), AREAS(7), PR12D(6), PR13D(6), ETARD(6)
COMMON DR(6), DS(6), DEQR(6), DEOS(6), BLOCK(6), BLOCKS(7)
COMMON BETIMR(6), BET2MR(6), PBET1MS(7), BET2MS(7), RADII(6), RADI2(6)
GAMMA = 1.0/(1.0 - RMIX/CPMIX/778.0)
G2 = (GAMMA - 1.0) / (1.0 - RMIX/CPMIX/778.0)
63 = -1.0/(GAMMA - 1.0)
MA1 = 0.5
RHOG1 = PRES/RMIX/TOIG
RHOGS = (1.0 + G2*MA1**2)**G3*RHOG1
RHOMS = 1.0/(1.0 - XWI)/RHOGS+XW1/RHOW
TS = TO1G/(1.0 + G2*MA1**2)
A = SORT(GAMMA*RMIX*TS*32.174)
C = HICASD(XW1, RHOGS, A)
IF(UPERM.NE.3) UZ = AMASSM/RHOMS/AREA1
IF(UPERM.EQ.3) UZ = AMASSM/RHOGS/AREA1
IF(AMASSM.LT.0.001) UZ = UTPG(ISTAGE)*FAI
ALFA = ALFA*3.1415927/180.0
MCI = UZ/C/COS(ALFA)
I1A2 = 0.6
RHOGS = (1.0 + G2*MA2**2)**G3*RHOG1
RHOMS = 1.0/(1.0 - XW1)/RHOGS+XW1/RHOW
TS = T01G/(1.0 + G2*MA2**2)
A = SORT(GAMMA*RMIX*TS*32.174)
C = HICASD(XW1, RHOGS, A)
IF(UPERM.NE.3) UZ = AMASSM/RHOMS/AREA1
IF(UPERM.EQ.3) UZ = AMASSM/RHOGS/AREA1
IF(AMASSM.LT.0.001) UZ = UTPG(ISTAGE)*FAI
MC2 = UZ/C/COS(ALFA)
J = J + 1
300 MANEW = WICNEW(MAI, MCI, MA2, MC2)
RHOGS = (1.0 + G2*MANEW**2)**G3*RHOG1
RHOMS = 1.0/(1.0 - XW1)/RHOGS+XW1/RHOW
TS = T01G/(1.0 + G2*MANEW**2)
A = SORT(GAMMA*RMIX*TS*32.174)
C = HICASD(XW1, RHOGS, A)
IF(UPERM.NE.3) UZ = AMASSM/RHOMS/AREA1
IF(UPERM.EQ.3) UZ = AMASSM/RHOGS/AREA1
IF(AMASSM.LT.0.001) UZ = UTPG(ISTAGE)*FAI
MCNEW = UZ/C/COS(ALFA)
ERROR = ABS(MANEW - MCNEW)
ERROR = ERROR - MANEW
EPS = 1.0E-6
IF(ERROR.LT.EPS) GO TO 200
MA1 = MA2
MCI = MC2
MA2 = MANEW
MC2 = MCNEW
J = J + 1
IF(J.LT.50) GO TO 300
WRITE(6, 403) ISTATE
403 FORMAT(1H0, #M2 DOES NOT CONVERGE AT STAGE==, I1)
GO TO 998
200 N = MANEW
IF(AMASSM.LT.0.001) ISTATE = 0
998 RETURN

C+++----------------------------------------------+++
CFUNCTION WICASD
C
FUNCTION WICASD ( XW, RHOG, CG )
RHOG = 62.2567
CU = 4956.04
UICASD SIGUIA = (XW * RHOC) / (RHOG - XW * (RHOG - RHOC))
A1 = (1.0 - SIGUMA) * RHOG + SIGUMA * RHOG
A2 = (1.0 - SIGUMA) / (RHOG + SIGUMA * RHOG)
A3 = SIGUMA / (RHOG * XW + CH)
A4 = A1 * (A2 + A3)
WICASD = 1.0 / SORT (A4)
RETURN
END

SUBROUTINE WICBA
    OMECAS, SIGUIA, BETIS, BET2S, AINCIS, ADEVIS, AMACH1,
    DEOS, SITACS, BET1X, AK1, AK3, UZ1, UZ2, UR1, R1, R2)
CALL WICDD(AK3, UZ1, UZ2, UR1, R1, R2, BETIS, BET2S, SIGUMA, OMEGAS,
    DEOS, SITACS)
AINCIS = BET1X + AINCIS - BET1X
BET2A = BET2S
XI = BET1X
DELEO = WICDD(AK3, UZ1, UZ2, UR1, R1, R2, BET1X, XW, SIGUMA, AINCIS, AINCIS)
ADEUI = ADEVIS + (6.40 - 9.45 * AMACH1 + 9.45 * X) * DELEO * AK1
IF (AMACH1 .LT. X) ADEUI = ADEVIS + 6.40 * DELEO * AK1
BET2C = BETES - ADEVIS + ADEVI
Y1 = BET2C
M = 1
IF (N.GT.1) GO TO 10
BET2A = BETES + 1.1
10 IF (N.GE.1) GO TO 12
BET2A = BET2S
DELEO = WICDD(AK3, UZ1, UZ2, UR1, R1, R2, BET1X, XW, SIGUMA, AINCIS, AINCIS)
ADEUI = ADEVIS + (6.40 - 9.45 * AMACH1 + 9.45 * X) * DELEO * AK1
IF (AMACH1 .LT. X) ADEUI = ADEVIS + 6.40 * DELEO * AK1
BET2C = BETES - ADEVIS + ADEVI
Y2 = BET2C
DELBET = ABS((X2 - Y2) / X2)
EPS = 1.0E-6
IF (DELBET .LE. EPS) GO TO 11
BET2A = WICNE(X1, Y1, X2, Y2)
X1 = X2
Y1 = Y2
M = M + 1
IF (N.GT.50) GO TO 13
GO TO 12
11 BET2A = X2
GO TO 15
13 WRITE (6, 201)
201 FORMAT (1X, 'DO NOT CONVERGE!')
15 RETURN
END

SUBROUTINE WICD
    OMEGAS, SIGUMA, BETIS, BET2S, AINCIS, ADEVIS, AMACH1,
    DEOS, SITACS)
C1 = 180.0 / 3.1415926
BETIS = BETIS / C1
BET2S = BET2S / C1
CSB1 = COS(BETIS)
CSB2 = COS(BET2S)
CSCS = CSB2 / CSB1
TBD1 = WICD(BETIS)
TBD2 = WICD(BET2S) * (U2 / V2) * (R2 / R1)
RETURN
WICDD

END

226
SUBROUTINE WICISS, ISTAGE, R, WX1, WX2, RHO1, ALPHA1, WI1, WI2, WI3, WI4

COMMON TD(7), IUNIT
COMMON CFL, CFT, CPF, CFD, CF, CFU, CFA
COMMON JERF, R-OG(3), RERUP, RERLDW, RESUP, RESLOW
COMMON PREB, FRTIP(8), SRTIP(8), AAA1, AAA2, AAA3, SAREA(6), SAREAS(7)
COMMON P(C3), TG(C3), XA, XV(3), XCH, XH(3), XW(3), XHT(3), TH(3), THW(3)
COMMON OMEG(C7), OMEG(6), GAPR(6), GAPS(6)
COMMON RRAUB(6), RC(6), RBLADE(6), STAGER(6)

RETURN

END

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C SUBROUTINE WICISS
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C SUBROUTINE WICISS
DS1 = (0.06 * SC (ISTAGE)) / 12.0
PAI = 3.1415926
B = 1.0

B2R = (90.0 - ALFA2 + STAGES (ISTAGE)) * PAI / 180.0
B2 = COS (B2R)
ALFA2 = ALFA2 * PAI / 180.0

DS2 = 2.0 * PAI / R / SBLADE (ISTAGE) * COS (ALFA2) / COS (B2R)

IF (DS2 > SC (ISTAGE)) DS2 = SC (ISTAGE)
H = (AAA2 * 144.0) / (2.0 * PAI * R)
A1 = DS1 + H * SBLADE (ISTAGE) / 144.0
A2 = DS2 + H * SBLADE (ISTAGE) / 144.0

W1 = LWC * U1 * B1 + A1
W2 = LWC * U1 * B2 + A2
W1 = W1 + W2

RETURN
C SUBROUTINE WICAK
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C SUBROUTINE WICAK
C C C C C

SUBROUTINE WICAK (RHOG, V, DWAKE, DWAKE1)

VISCOF = 1.20E-3
SIGMA = 4.6534E-3
CC = 32.174
W-E = 21.0

SN = VISCOF * 2 / (RHOG * SIGMA / DWAKE1)

W-E = 22.0

IF (DIAKE = (HE * SIGMA / CC) / RHOG / V ** 2)

SN = VISCOF ** 2 / (RHOG * SIGMA * DIAKE1 * CC)

HELMIT = 12.0 * (1.0 * SN ** 0.56)

DIAKE2 = DIAKE1 * DIAKE2 / D2

SN = VISCOF ** 2 / (RHOG * SIGMA ** 0.0 * CC)

HELMIT = 12.0 * (1.0 * SN ** 0.56)

DWAKE = HELMIT * SIGMA / CC)

SN = VISCOF ** 2 / (RHOG * SIGMA * XXX / CC)

HELMIT = 12.0 * (1.0 * SN ** 0.56)

DWAKE = HELMIT * SIGMA / CC)

DWAKE1 = CWE * SICUMA * CC) / (RHOG * V ** 2)

SN = UISCOF * 2 / (RHOCSIUIA * DWAKE1 * CC)

WELIMT = 12.0 * (1.0 + SN ** 0.36)

FLI = WELIMT * SIGMA * CC / (RHOC * V ** 2)

W = 22.0

DWAKE2 = (WE * SIGMA * CC) / (RHOG * V ** 2)

SN = UISCOF ** 2 / (RHOCSIUIA * XXX * CC)

WELIMT = 12.0 * (1.0 + SN ** 0.36)

W.ELIT = 12.0 * (1.0 + SN ** 0.36)

DWAKE = WELIT * SIGMA * CC / (RHOC * V ** 2)

DWAKEM = DWAKE / 3.2802 * 1.0E6

RETURN
END

SUBROUTINE WICHET

DIMENSION DELHET(51)

REAL ND

IF (I4MASSI < 1.0E-6)

PAI = 3.1415927

DAUEA) = (DAUEN2 + DAUEN) / 2.0 * 1.0E-6 * 3.2802

IF (DAUEA < 1.0E-6)

RHOW = 62.54

RMASSI = (DAUEA / 4.0 / 3.0 / PAI * (DAUEN / 2.0) ** 3)

KA = 0.015 / 3600.0

PR = 0.7

M = 2.0 * 0.6 * SORT (RE) * PR ** 0.33

HCONVE = KA / DAUEA / NU

J = 1

10 DELT = (TCl - TWI + (TC3 - TW3)) / 2.0

DELTH = HCONVE * 4.0 / (DAUEA / 2.0) ** 2 * DELT

ND = DELT / VZ

CM ASSI = WMASS1 + WMASS + AMASS + CHMASS + CPF + CPW

DELTH = DELTH / CMASS + CPF

DELTH = DELTH / CMASS

TG3 = TG3 - DELTH

J = J + 1

IF (J <= 2) GO TO 10

EPOR = ABS (DELHET (J) - DELHET (J-2))

EPS = 0.0001

IF (EPOR > EPS) GO TO 11

RETURN

END
SUBROUTINE I4ICMAS
SUBROUTINE WICMTR(H1, TW1, PW1, PW2, UZ1, UZ2, DZ1, DZ2, PW1, PW2, PW1, PW2, UZ1, UZ2, DDAVE1, DDAVE2, WM1ASS1, WM1ASS2, DMTAV, AMASS1, AMASS2, DMDTAU, AMASS, RE)
PW1 = WICPWB(TW1)*144.0
PW2 = WICPWB(TW2)*144.0
PW1 = (H11 + PW1) / (H11 + 0.6219)

DMTAV = (DMT1 + DMT2) / 2.0
UMASS2 = WM1ASS1 + DMTAV
WM1ASS2 = WM1ASS1 - DMTAV
H2 = UMASS2 / AMASS
W2 = PW1 + PW2 / (H2 + 0.6219)

PW2AS2 = 1.05

DMT2 = WICMTR(TG2, TH2, PW2, DDAVE2, UZ2, DZ2, WM1ASS2)

PW2AS2 = PW2AS1

DMT2 = WICMTR(TG2, TH2, PW2, DDAVE2, UZ2, DZ2, WM1ASS2)

PW2AS2 = PW2AS1

PW2AS2 = PW2AS1

I1AS2 = WICMTR(TG2, TH2, PW2, DDAVE2, UZ2, DZ2, WM1ASS2, PW1, PW2, PW1, PW2, UZ1, UZ2, DDAVE1, DDAVE2, WM1ASS1, WM1ASS2, DMTAV, AMASS1, AMASS2, DMDTAU, AMASS, RE)

DMTAV = (DMT1 + DMT2) / 2.0
UMASS2 = WM1ASS1 + DMTAV
WM1ASS2 = WM1ASS1 - DMTAV
H2 = UMASS2 / AMASS
W2 = PW1 + PW2 / (H2 + 0.6219)

PW2AS2 = PW2AS1

PW2AS2 = PW2AS1

I1AS2 = WICMTR(TG2, TH2, PW2, DDAVE2, UZ2, DZ2, WM1ASS2, PW1, PW2, PW1, PW2, UZ1, UZ2, DDAVE1, DDAVE2, WM1ASS1, WM1ASS2, DMTAV, AMASS1, AMASS2, DMDTAU, AMASS, RE)

DMTAV = (DMT1 + DMT2) / 2.0
UMASS2 = WM1ASS1 + DMTAV
WM1ASS2 = WM1ASS1 - DMTAV
H2 = UMASS2 / AMASS
W2 = PW1 + PW2 / (H2 + 0.6219)

ERROR = ABS(PW2AS2 - PW2AS2)
EPS = 0.01
IF(ERROR.GT.EPS) GO TO 2

RETURN

END

FUNCTION WICMTR(TG, TH, PW, DAVE, UZ, DZ, WM1ASS, PW, RE)
REAL KG, ND, MM1ASS
IF(DAVE.LT.1.0E-6) WICMTR=0.0
IF(DAVE.LT.1.0E-6) CO TO 10
DD = DAVE#1.0E-6*3.2802
T = (TT + TT) / 2.0
P1 = 3.14*3926
P0U = 62.2587
*R = DD / P.0
T = T * 5.0 / 3.0
*P = PPP * 476.80258
D0 = 4.2402893*(TT**1.5)/PP
SCT = 0.60
SF=2.0*0.60*SORT(RE)*SCT**0.33
KG = DU / DD * SH
WICMTR 21


```
C **----------------------------------------------------------------------------------**
C FUNCTION WICPWB
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
FUNCTION WICPWB(TWB)
TSTAG=TWB
TSTAGC=(TSTAG-492.0)/1.8
IF((TSTAGC.LT.100.0) OR (TSTAGC.GT.200.0)) GO TO 41
A=5.45142
B=2010.8
GO TO 42
40 A=5.9778
B=2224.4
GO TO 42
41 A=5.6485
B=2101.1
42 AA=A-B/(TSTAGC+273.0)
PS=10.0**AA
PS=PS/4.*8.8247E-4
WICPWB=PS/144.0
RETURN
END WICPWB

C **----------------------------------------------------------------------------------**
C FUNCTION WICNEW
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
FUNCTION WICNEW(X1,Y1,X2,Y2)
T=ABS((X2-X1)/X1)
IF(T.LT.1.0E-6) WICNEW=(Y1+Y2)/2.0
IF(T.LT.1.0E-6) GO TO 100
A=(Y2-Y1)/(X2-X1)
D=Y1-A*X1
WICNEW=B/(1.0-A)
100 RETURN
END WICNEW

C **----------------------------------------------------------------------------------**
C FUNCTION WICBPT
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
FUNCTION WICBPT(TSTAG,PSTAG)
TSTAGC=(TSTAG-492.0)/1.8
IF((TSTAGC.LT.100.0) OR (TSTAGC.GT.200.0)) GO TO 21
A=5.45142
B=2010.8
GO TO 22
20 A=5.9778
B=2224.4
GO TO 22
21 A=5.6485
B=2101.1
22 PS=PSTAG*4.88247E-4
TBOILK=E/(A-ALO-710(PS))
WICBPT=TBOILK*1.8
RETURN
END WICBPT
```
CFUNCTION WICSH
FUNCTION WICSH(TSTAG,PSTAG)
TSTAGC=(TSTAG-422.0)/1.8
IF(TSTAGC.LT.100.0.AND.TSTAGC.LT.200.0) GO TO 40
A=5.45142
B=2010.8
GO TO 42
40 A=5.9778
B=2224.4
GO TO 42
41 A=5.6485
B=2101.1
GO TO 42
42 AA=A-B/(TSTAGC+273.0)
PS=10.0**AA
PS=PS+4.88247E-4/(PSTAG-PS)
RETURN
END

CFUNCTION WICTAN
FUNCTION WICTAN(X)
A=COS(X)
B=SIN(X)
WICTAN=B/A
RETURN
END

C SUBROUTINE WICCEN
SUBROUTINE WICCEN(RZERO,UZERO,DD,UZDEL,ALFAA,IRHUB,DU,ALFAAR,UA,PN,TAU)
REAL N
PAI=3.1415926
ALFAAR=ALFAA*PAI/180
IF(DD.LT.1.OE-6) GO TO 12
F=DD*1.0E-6*3.2802
RHOD=62.37
XAA=XAX/G
XCU=CH4/XG
XCC=CH4/XG
VISCO=(XXAA*0.05715+XXU*0.03293+XCC*0.035)/3600.0
ENDTM=DELZ/VZ
JJ=10
DELTM=ENDTM/FLOAT(JJ)
R1=RZERO
U1=UZERO
TIME=0.0
JJ=1
11 RE=D*U/VISCO
B1=0.44
N=0.0
IF(RE.LT.1.0) B1=0.4
IF(RE.LT.1.0) N=1.0
IF(RE.GT.1.5.AND.RE.LT.500.0) B1=18.5
IF(RE.GT.1.5.AND.RE.LT.500.0) N=0.6
RETURN
END

233
SUBROUTINE WICDML( IPRINT, IRADPAMASW1, AMASHT, AMASH2, R1, R2, STARER, $RSTAUE, RTIP, DMIN, DMOUT, AMASW2, DMOUTC)

FAI=3.1415926
FSTI=RSTAUE
A1=STARER
A2=PAI*(R2**2-R1**2)/144.0
H=R2*0.5
DMCENT=42/A1*AMASH
120 IF(DMCENT.LT.0.0) DMCENT=0.0
IF(DMCENT.GT.RHOD) DMCENT=AMASH
RETURN
GO TO 110

DMN=DMCENT
DMOUT=DMCENT
GO TO 100

CONTINUE
DMN=0.0
DMOUT=DMCENT
100 IF(NDIENT.EQ.1) DMOUT=0.0
IF(NDIENT.EQ.3) DMIN=0.0
AMASH2=AMASH1+DMIN-DMOUT
IF(AMASH2.LT.0.0) AMASH2=0.0
IF(AMASH2.GT.RHOD) AMASH2=AMASH
DELMAS=AMASH2-AMASH
IF(NDIENT.EQ.2) WRITE(6,200) AMASH2, AMASH1, DMIN, DMOUT, DMCENT
RETURN
END

C======================================================================================================


C SUBROUTINE WICDML

C======================================================================================================

C****************************************************************************************************

C****************************************************************************

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C******************************************************************************
RST1=RSTAVE
AL=STAREA
A2=PAI*(R2**2-R1**2)/144.0
h2=A2*0.5
DINCENT=A2/R1*AMASW
120 IF(DINCENT.LT.0.0) DINCENT=0.0
INCDENT
DMIN=AMASW
DMOUT=DINCENT
GO TO 100
110 CONTINUE
DMIN=0.0
DMOUT=DINCENT
100 IF(IFRAD.EQ.1) DMOUT=0.0
IF(IFRAD.EQ.3) DMIN=0.0
AMASW2=AMASW1+DMIN-DMOUT
DAMAS=AMASW2-AMASW1
IF(IPRINT.EQ.2) WRITE(6,200) AMASW2,AMAS1,DMIN,DMOUT,DINCENT,
$AMASWT,AMASW,DELMAS
200 FORMAT(IHO,8(F10.5,3X))
RETURN
END
C ......
C SUBROUTINE WICDRG
C SUBROUTINE WICDRG(D,DELV1,RHGA1,RHGA2,CD2,DELV2,DRAG1,RE)
REAL N1
GC=32.174
IPRINT=1
VISCUG=12.0E-6
PAI=3.1415927
IF(D.GT.0.0) GO TO 300
CD2=0.0
DRAG1=0.0
GO TO 301
300 REI=(RHGA1*D*DELV1)/VISCUG
RE=REI
B1=0.44
M1=0.0
IF(RE.LT.1.9) B1=24.0
IF(RE.LT.1.9) M1=1.0
IF(RE.LT.1.9.AND.RE.LT.500.0) B1=18.5
IF(RE.LT.1.9.AND.RE.LT.500.0) M1=0.6
CD1=B1/(RE**M1)
DRAG1=0.5*RHGA1*(CD1*0.5*RHGA2*(PAI*D**2))
$GC
CDM=DRAG1*GC/(CD1*0.5*RHGA2*(PAI*D**2))
IF(IPRINT.EQ.2) WRITE(6,101) D,DELV2,RHGA1,RHGA2,RE1,B11,M1,
$CD1,DRAG1,CDM
200 FORMAT(IHO,10(F10.5,2X))
DELV2=SORT(DAMY)
RE2=RHGA2*D*DELV2/VISCUG
B1=0.44
M=0.0
IF(RE2.LT.1.9) B1=24.0
IF(RE2.LT.1.9) M=1.0
IF(RE2.LT.1.9.AND.RE2.LT.500.0) B1=18.5
IF(RE2.LT.1.9.AND.RE2.LT.500.0) M=0.6
CD2=B1/(RE2**M)
C IF(IPRINT.EQ.2) WRITE(6,101) RE1,B11,M1,CD1,DELV1,RE2,B1,M,CD2,
$DELV2
101 FORMAT(IHO,2X,10(F10.5,2X))
SUBROUTINE WICSIZ

TMASSI = WMASSL + WMASSS + AMINC1 + AMING2 + AMING3

AMLO = 0.0

IF (DL.GT.DLIMIT) AMLO = AMLO + WIASSL
IF (DL.LT.DLIMIT) AMS = AMS + WIASSL

IF (DL.GT.DLIMIT) AMS = AMS + AMING1
IF (DL.LT.DLIMIT) AMS = AMS + AMING2
IF (DLG.T.GT.DLIMIT) AMS = AMS + AMING3

IF (DS.GT.DLIMIT) AMS = AMS + AMING1
IF (DS.LT.DLIMIT) AMS = AMS + AMING2
IF (DSG.T.GT.DLIMIT) AMS = AMS + AMING3

IF (D2.GT.DLIMIT) AMS = AMS + AMING1
IF (D2.LT.DLIMIT) AMS = AMS + AMING2
IF (D2G.T.GT.DLIMIT) AMS = AMS + AMING3

IF (D3.GT.DLIMIT) AMS = AMS + AMING1
IF (D3.LT.DLIMIT) AMS = AMS + AMING2
IF (D3G.T.GT.DLIMIT) AMS = AMS + AMING3

TMPSS2 = AMS + TMASS2
ERROR = ABS(TMASS2 - TMASS2)

IF (ERROR.LT.1.0E-6) GO TO 100
IF (ThASS2.LT.1.0E-6) GO TO 100

TT = TMASS2 + TMASS2
IF (TT.LT.1.0) AT1 = ATL + TT
IF (TT.LT.1.0) ANS = ANS + TT
IF (TT.GT.1.0) ATL = ATL * TT
IF (TT.GT.1.0) ANS = ANS * TT

DLCE = ADL
DSLL = ADS

IF (DL.LT.0.0.AND.DLCE.GT.DL) DLCE = DL
IF (DS.LT.0.0.AND.DSLL.GT.DS) DSLL = DS

RETURN
END WICSIZ
CPRX=XXAIR+XH2O+XICCPA(T)+XXCH4+XICCPA(T) WICRP 18
GAMMA=1.0/(1.0-RMIX/CPRX/776.0) WICRP 19
G1=GAMMA/(GAMMA-1.0) WICRP 20
G2=(GAMMA-1.0)/2.0 WICRP 21
G3=-1.0/(GAMMA-1.0) WICRP 22
RETURN WICRP 23
END WICRP 24

GAMMA=(1.0/(1.0-RMIX/CPIIX/778.0) WICPRP 1
GI=CAIM/(GAMMA-1.0) UICPRP 20
G2=(GAMMA-1.0)'2.0 WICPRP 21
G3=-1.0/(GAMMA-1.0) RETURN WICPRP 23
END WICPRP 24

FUNCTION WICCPA
RETURN
END WICCPA

FUNCTION WICCPA(T)
RETURN
END WICCPA

FUNCTION WICCPH
RETURN
END WICCPH

FUNCTION WICCPH(T)
RETURN
END WICCPH

FUNCTION WICCPH4
RETURN
END WICCPH4

FUNCTION WICGSL
RETURN
END WICGSL

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C SUBR~OUTINE WICCSL
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CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
SUBROUTINE WICGSL(OtIEGASPSIGUIIABET1S.DET2SAINCISADEISPAIACH1
IBETIDEOS. DEON,SJTACS, SITACNBET2t.OEGAt1pXP IDESINiAKIAK2,AK3
2 U, Z22 URi ,RI R2)
CALL ICEDDAK3,UZ1.UZ2,URl.Rl.R2,BETSBET2SSIGI1A.OtEGAS,
$DEGStSITACS)
AINCI=BETI-BETIS*AINCIS
BET2A=BET2S
XI=BET2A
DELDEQ=WICED(AK3,UZ1,UZ2.UIR1.R1,R2.BETI.XsSIGU1AAIMCISPAIMCI)
$-DEUS
ADEUI=ADEVIS+(6.40-9.45*A1ACHi+9.45*X)*DELDEO.AK1
IF(AMACH1 .LT.X) ABEtJI=ADEUIS+6.40.DELDEQOAKI
BET2C=BET2S-ADEUIS+ADEVI
Yl=BET2C
ri~i
12 IF(N.GT.1) GO TO 10
BET2A=BET2S*1.*1
10 X2=BET2A
DEON=WICED(AK3.UZ1,VZ2,URl.RlR2.DET1.X2SIGUIA.AIMCISPAIMCI)
DELDEG=DEON-DEGS
ADEUI=ADEVIS+(6.40-9.45*AIACH1+9.45*X)*DELDEO.*AKI
IF(AtIACHI .LT.X) FiEUI=ADEUIS+6.40*DELDEO*AKI
EET2C=BET2S-ADEUIS+ADEUI
Y2=BET2C
DELBET=ABS( (X2-Y2)/X2)
EPS=1.OE-6
IF(DELBET.LE.EPS) GO TO 11
BET2A=WICMEW(X1,YIPX2vY2)
>X1=X2
V 1=Y2
N=N+1
IFlrl.GT.50) GO TO 13
CO TO 12
11 BET2N=X2
GO TO 14
13 WRITE(69201)
201 FORMAT(1H0,oDO NOT CONVERGE$)
GO TO 15
14 SITACN4JICf1TK(SITACSAMACH1I DELDEOAK2)
OMEGAN41ICLOS(BET1I DET2Nl.SIGUMA, SITACN)
SSS=SI TACN-SITACS
15 RETURN
END

WICGSL
IJICGSL
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WICGSL
I4ICGSL
WICGSL
LJICGSL
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W.ICGSL
I4ICGSL
WICGSL
LJICGSL
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WICSDL
SUBROUTINE LICSL(CHORD,SIGUMA.DETA1.DETA2*UG.RHOGv
$ArIASSW, AREA, UZ, IPRINT. OfEGAP)
WICSDL
PAI=3. 1415926
IJICSDL.
WICSDL.
RHOGO=RHOG
RHOPO=AMASSW/AREA/VZ
WIcSDL
UXCSDL
RR=RHOPO/RHOGO
I4ICSDL
VISCOGo0. 128E-4
IJICSDL
C=CHORD/12. 0
WICSDL
RE=UG*C*RHQO/VISCOG
WICSDL
DELC=0.37/(RE**0.2)/( 1.0+1.442.RR)**0.8
WICSDL
DELP0. 1402*DELC
WICSDL.
BETA1R=BETA1'PAI/180.*0
WICSDL
BETA2R=BETA2*PAI/180.*0
UICSDL
OMEGAP=DELP*2.0*SIGUfACOS(E.'MR'.CCOS(BETA1R)/COS(BETA2R) )**2
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IICSDL.
END
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SUBROUTINE WICSTL(ISTAGE, IROTOR, DAU, U1, U2, DELU, U3, WM, DELU2, DELU2,
  $, BETAL, BETA2, ALFA2, ALFA3, M4M, DELUE2, DELU2,
  $OMEGRU, OMEGRL, OMEGSU, OMEGSL, DRAGRU, DRAGRL, DRAGSU, DRAGSL, REAVE)
REAL M, WM
COMMON TD7, TD77
COMMON CFL, CFT, CFM, CFU, CFA
COMMON JPERF, RHQ(3), RERUP, RERLOW, RESUP, RESLO
COMMON PREBRRTIP(8), SRTIP(8), AAA1, AAA2, AAA3, SAREA(6), SAREAS(7)
COMMON P(3), TG(3), PXAXIJ(3), XW(3), XWW(3), XWT(3), TW3(3), FS(3)
COMMON OMEGRS(7), OMEGR(6), CAPR(6), GAPS(6)
COMMON RRHUB(6), SC(7), SBLADE(7), PSTAGES(7)
COMMON SIGUMR(G), BRET1SR(6), BRET2SR(6), ATINCSR(6), ADEVSR(6)
COMMON SIGUMS(7), BRET1SS(7), BRET2SS(7), ATINCSS(7), ADEVSS(7)
COMMON UTIPC(6), UTIP(6), UTIPD(S), U0U(6),-UA2(6), UHUB(6), UHUB2(6), IPRI
COMMON AREA(6), AREAS(7), UU2(6), UTIP2(6), UHUB(6), UHUB2(6), IPRI
COMMON ICENT, ICENTFMR1(6), FMA2(6), IDEIN, FAID
COMMON NS, NSI, RT(6), RM(6), RH(6), ST(6), SH(6), SH(6)
COMMON DSMASS, AAREA(7), AAREAS(7), PR12D(6), PR13D(6), ETARD(6)
COMMON LR(), S(6), DEQR(6), DEOS(6), BLOCK(6), BLOCKS(7)
COMMON BET1IR(S), BET2MR(S), BET1IS(7), BET2MS(7), RADI1(6), RADI2(6)
P1A=3.1415927
GC=32.174
RHOIJ=62.3
IF (IROTOR.EQ.2) GO TO 100
C DROPLET DRAG IN ROTOR
DD=DAU*1.0E-6*3.28
UG1=W1
UP1=UG1-DELU
Al=IJMASS*RC( ISTAGE)/12.0/LZ
A2=RHOW*4.0/3.0*PAI*(DD/2.0)**3
TMO0.0
IF(WMASS.GT.0) GO TO 2000
GO TO 2001
2000 TN=Al/A2
NM=INV+2.0
CMUI=(90.0-BETA1 )/2.0*PAI/180.0
DELUI=UG1-UP1*CMUI
IF(N.GT.2) DELUI=DELU2
TM=TN*(180.0-BETA1-BETA2)/360.0
XW(2)=XW(1)
XWT(2)=XWT(1)
CALL WICPRP(XA, XU(2), XCH4, TG(2), RMIX, CMPIX, GAMMA(1), GM, G3)
IF(IPRINT.EQ.2) WRITE(6, 4000)
4000 FORMAT(1H0, "DROPLET DRAG IN ROTOR (UPPER PART)"
CALL WICGR(DD, DELUI1. RHOG(1), RHOG(2), CO2, DELU2, DRAG1, RE)
DELU2=DELU2
CDRI=CO2
KERUP=RE
DRAGU=DRAG1*TNU
AREA=PI*(RTIP(ISTAGE)**2-RRHUB(ISTAGE)**2)/144.0/10.0
DELU1=DRAGU/AREA1
OMEGU=DELU1/0.5*RHOG(1)/GC+UI**2)
CDRI=CDRI*DELU1
DELU1=UG1-UP1*CMUI
IF(N.GT.2) DELU1=DELU2
TM=TN*(180.0-BETA1-BETA2)/360.0
IF(IPRINT.EQ.2) WRITE(6, 4001)
4001 FORMAT(1H0, "DROPLET DRAG IN ROTOR (LOWER PART)"
CALL WICGR(DD, DELU1, RHOG(1), RHOG(2), CO2, DELU2, DRAG1, RE)
DELU2=DELU2
CDRI=CO2
KERUP=RE
DRAGU=DRAG1*TNU
DELPR=DRAG1*AREA1
239
OEGRL=DELPL/(0.5*RHOG(1)/SC*W1**2)

CDRL=CDRL+DELUL2**2*PAI/4.0**2/TML/VAUE**2/RC(ISTAGE)*12.0

2002 FORMAT(H0,*DROPLET DRAG SUMMARY*)

IF(IPRINT.EQ.2) WRITE(6,2002) DELUL2,DELUL2,DELUL2,CDRL,CDRL

720 FORMAT(H0,10(F10.5,2X))

RUP1=(90.0-BETA1)/180.0
RL0W1=(90.0+BETA1)/180.0
RUP2=(90.0-BETA2)/180.0
RL0W2=(90.0+BETA2)/180.0

2010 FORMAT(H0,*DROPLET DRAG IN STATOR )

GO TO 200

C DROPLET DRAG IN STATOR

DD=DAU*1.0E-6*3.28

VPI=U1-DELU

A1=WRIAS*SC(ISTAGE)/12.0/U1

A2=RHOW*4.0/3.0*PAI*(DD/2.0)**3

TNU=ALFA2*180.0/360.0

DELPSU=DRAGSU/TNU

OMEGSU=DELPSU/(0.5*RHOG(2)/SC*U2**2)

CDSU=CDSU*DELUL2**2*PAI/4.0**2*TNU/VAUE**2/SC(ISTAGE)*12.0

DELUL1=DELUL2

TNL=TFI*(180.0+ALFA2+ALFA3)/360.0

IF(IPRINT.EQ.2) WRITE(6,2007) DELUL1,DELUL2,CDRL,CDRL

SUPI=(90.0+ALFA2)/180.0

SLOW1=(90.0-BETA3)/180.0

SUP2=(90.0-BETA2)/180.0

RESLOW=RESUP*(SUP1+SUP2)*0.5+RESL0W*(SLOW1+SLOW2)*0.5

2008 FORMAT(H0,*DROPLET DRAG IN STATOR (SUMMARY*))

IF(IPRINT.EQ.2) WRITE(6,2008) SUP1,SUP2,SLOW1,SLOW2

2011 FORMAT(H0,*DROPLET DRAG IN STATOR )

GO TO 200

END

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C SUBROUTINE WICFML

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PAI = 3.1415927
ALPHA = ALFA * PAI / 180.0
V1 = UZ / COS(ALPHA)
V2 = UZ * TAN(ALPHA)
V3 = (UCYSTAGE) - V51
T = W1 / U*
BETAI = ALFA * PAI / 180.0
I T = UZ = W2 = W1 = *2
W1 = SQRT(TT)
MAC3 = UZ / ASCED
CALL WICSD(IOMES,ISTAGE), SIGMA (ISTAGE), BETISR (ISTAGE)
RETURN
1 AIICSP (ISTAGE), ADEUSP (ISTAGE),
1 IMACCI, BE1AI, D09, DE0N+STAGES, SATCN, BETEN, FARI (ISTAGE),
10 (BUAS, UZ, UZ, UZ, UZ, UZ), RADI1 (ISTAGE), RADI2 (ISTAGE))
ISTAGE = BETEN
BETAR = BETAR = PAI / 180.0
V52 = UZ = TAN (BETAR)
V53 = (UCYSTAGE) - V52
T155 = UZ = W2 = W1 = *2
MAC3 = UZ / ASCED
CALL NLBO (OMES, ISTAGE), SIGMA (ISTAGE), BETISS (ISTAGE),
1 JIES1 (ISTAGE), AIICSP (ISTAGE), ADEUS1 (ISTAGE),
1 IMACCI, ALFA, D09, DE0N+STAGES, SATCN, BETEN, FARI (ISTAGE),
10 (BUAS, UZ, UZ, UZ, UZ, UZ), RADI1 (ISTAGE), RADI2 (ISTAGE))
FAR3 = BETEN
ALFAR = ALFAR = PAI / 180.0
V55 = UZ = COS(ALFAR)
RETURN
END
ISTAGE=N1
CALL WICPP(1.0,0.0,0.0,TG(1),RMIX,CMPMIX,GAMMA,G1,G2,G3)
CALL WICMAC(ISTAGE,ARIASS,TG(1),P(1),M,U2,C,0.0,0.0,RMX,CMPMIX,ARE
SING(NG1))
UZIN=UZ
HI=HI
IZIN=IZIN
TOIN=TG(1)
POIN=POIN
PSIN=PSIN
TSM=TSIN
FRAIN=UZIN/UTICP(1)
FAID=FAID
CVMAG=GAMMA
TOIN=TG(1)
POIN=POIN
CIV U INLET PRIN/OUT
IF(NUNIT.NE.2) GO TO 851
TOIN=TOIN
ETC P
POIN=POIN
PSIN=PSIN
TSM=TSIN
FRAIN=FAID
UZIN=UZIN
AREAS(NS1)=AREAS(NS1)/CFA
851 CONTINUE
8161 CONTINUE
85 2 CONTINUE
1000 FORMAT(1X,40X,85) DESIGN POINT INFORMATION ************
82 CONTINUE
85 3 CONTINUE
1010 FORMAT(6,10I0) *********** COMPRESSOR INLET ******
85 4 CONTINUE
1020 FORMAT(11X,40X) TOTAL TEMPERATURE AT COMPRESSOR INLET=#,F10.5,/
85 5 CONTINUE
1030 FORMAT(11X,40X) ACOUSTIC SPEED AT COMPRESSOR INLET=#,F10.5,/
85 6 CONTINUE
1040 FORMAT(11X,40X) ACOUSTIC VELOCITY AT COMPRESSOR INLET=#,F10.5,/
85 7 CONTINUE
1050 FORMAT(11X,40X) mach NUMBER AT COMPRESSOR INLET=#,F10.5,/
85 8 CONTINUE
1060 FORMAT(11X,40X) FLOW COEFFICIENT AT COMPRESSOR INLET=#,F10.5,/
85 9 CONTINUE
1070 FORMAT(11X,40X) IF(NUNIT.NE.2) GO TO 852
86 CONTINUE
C ROTOR INLET
87 CONTINUE
ISTAGE=1
100 IF(1.E0.0) I=NS1
101 A1=ALFA1-DETS1)
102 DEVS1=ALFA1-DETS1)
103 CALL WICMAC(ISTAGE,ARIASS,TG(1),P(1),M,U2,C,0.0,ALFA1,RMX,
104 CMPMIX,AREAS(ISTAGE))
105 CMI=CMPMIX
106 CAV1=GAMMA
107 U2=U2
108 A1=C
109 NS1=P(1)*(1.0+G2*M1**2)**G1
TSM=TS1=(1.0+G2*M1**2)**G1

243
RHOGS1=PS1/RMIX/TS1
FAIRIN=U21/UTIP(ISTAGE)
ALFAI=ALFA1-PAI/180.0
U1=U1/COS(ALFAI)
VS1=U1*WICTAN(ALFAI)
W1=U1(ISTAGE)-VS1
W1=VS1/U1
BETAI=ATAN(UU)
BETAI=ALFAI*180.0/PAI
BETIR(ISTAGE)=BETAI
AINCST(ISTAGE)=BETAI-BETIMR(ISTAGE)
W1=U1/COS(BETAI)
M1REL=W1/A1
TREL1=(1.0+G2*M1REL**2)*TSI
PREL1=(1.0+G2*M1REL**2)**G1*PS1
IF(ISTAGE.GE.2)
DS(ISTAGE-1)=1.0-UI/U2.ABS(US2-US1)/2.0/
SICUMS(ISTAGE-1)/U2
IF(ISTAGE.GE.2)
DEOS(ISTAGE-1)=-COS(ALFAI)/COS(ALFA2R)*
$(1.12+0.61*COS(ALFA2R)**2'SIGUMS(ISTAGE-1)*(WICTArI(ALFA2R)-
S$IICTAN(ALFAI))
IF(ISTAGE.GT.1S)
GO TO 101
C ROTOR OUTLET
P(2)=PR12D(ISTAGE)*P(1)
TR12=(PR12D(ISTAGE)**(1.0/G1)-1.0)/ETARD(ISTAGE)+1.0
TC(2)=TR12*TC(1)
CALL IICPRP(1.0,0.0,0.0,TQC2)O RMIXCPMIX.GArIMAG1,G2,G3)
GAMMA2=GAMMA
CPMIX2=CPMIX
GAMMA=(GAMMA1+GAMMA2)/2.0
CPMIX=(CPMIX1+CPMIX2)/2.0
G1AU=GAMMA/((GAMMA-1.0)
G2AU=(GAMMA-1.0)/2.0
PRI31I=(TG(2)-TG(1))**G1AU
DELT=TG(2)-TG(1)
US2=(U(ISTAGE)*US1-'DELT*CPiIXUOCC*AJ)/UU2
US2=US2/UZ2AS
ALFA2R=ATAN(CUS2U'2)
ALFA2=ALFA2R*180.0/PAI
BET2SR (ISTAGE)=ALFA2
AINTSR(ISTAGE)=ALFA2-BET2MR(ISTAGE)
U2=UZ2AS/COS(ALFA2)
W2=UZ2AS/CCS(BETH2R)
TS2=TC(2)-U2**2/(.*0*CPMIX2*GC*AJ)
A2=SGRT(CCAM2*PMIXTS2*GC)
2U2/A2
PS2=P(2)/(1.0+C2*M2**2)**G1
RHOGS2=PS2/RMIX/TS2
M2REL=U2/A2
TREL2=(1.0+G2*M2REL**2)*TS2
PREL2=(1.0+M2REL**2)**G1*PS2
VZ2CL=I MASS/(RHOGS2*AREA(ISTAGE))
EPS=1.0E-6
IF(JJ.EQ.2) GO TO 201
IF(JJ.GT.2) GO TO 202
X1=U2AS
Y1=U2CL
V2AS=V2AS
JJA=J+1
GO TO 200
201 X2=U2AS
Y2=U2CL
V2AS=WICNEW(X1,Y1,X2,Y2)
JJ=JJ+1
GO TO 300

202 IF((AEG5)*(UZ2AS-UX2CL)/UX2AS),LT,EPS) GO TO 300
X1=V2
Y1=V2
X2=UX2AS
Y2=UX2CL
UX2AS=WIC84(X1,Y1,X2,Y2)
JJ=JJ+1
GO TO 200

300 UX2CL=WIC84(X1,Y1,X2,Y2)
FAIC44=UX2CL/UTPC(I8TAGE)
WIC5PD(AEG5-1.0-UX2CL),=UX2AS-UX2AS
WIC5PD(AEG5-1.0-UX2CL),=UX2AS-UX2AS
FAIC45=UX2CL/UTPC(I8TAGE)
WIC5PD(AEG5-1.0-UX2CL),=UX2AS-UX2AS
GO TO 300
1110 FORMAT(1H0, 1X, #ROTOR INLET#, 1X, 5(F10.3, 3X))
WRITE(6, 1120) TG(2), P(2), TS, PS, RHOGS
1120 FORMAT(1H0, 1X, #ROTOR OUTLET#, 5(F10.3, 3X))
WRITE(6, 1111)
1111 FORMAT(1H0, 1X, #ROTOR OUTLET#, 5(F10.3, 3X))
WRITE(6, 1180)
I=ISTAGE
IF(IUNIT.NE.2) GO TO 864
TG(1)=TG(3)
246
C OVERALL PERFORMANCE AT DESIGN POINT

101 QUALMT=F(C)-P0IN
QUALMT=G(3)/108N
CANNAV=(CANNAV+CANNAV)/2.0
GAIN=CANNAV/(CANNAV-1.0)
QUALI=(QUALI-1.0)/QUALMT-1.0)

C PRINTOUT OF OVERALL PERFORMANCE AT DESIGN POINT:

IF(IUNIT.NE.2) GO TO 665
1IN=T0IN(1)-CFT
QUALI=QUALI/CFT

422 CONTINUE
465 CONTINUE
WRITE(6,1000)
WRITE(6,421)
 WRITE(6,429)
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TD(I) = TD(I) * CFT

CONTINUE

RETURN

END
APPENDIX 5

PRINTOUT OF TEST CASE
A.5.1 Test Case Part I
**INPUT DATA**

**NS (NUMBER OF STAGE)= 6**

UNIT=ENGLISH UNIT

IPERF=2

PERFORMANCE AT MEAN

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251
********** INPUT DATA **********

FNF (FRACTION OF DESIGN CORRECTED SPEED) = 1.000
XDIN (INITIAL WATER CONTENT OF SMALL DROPLET) = 0
XDIN (INITIAL WATER CONTENT OF LARGE DROPLET) = 0
RHUMID (INITIAL RELATIVE HUMIDITY) = .00 PER CENT
XCH4 (INITIAL METHANE CONTENT) = 0

tog (COMPRESSOR INLET TOTAL TEMPERATURE OF GAS) = 518.70
TOW (COMPRESSOR INLET TEMPERATURE OF DROPLET) = 513.70
PO (COMPRESSOR INLET TOTAL PRESSURE) = 2116.80

DDIN (INITIAL DROPLET DIAMETER OF SMALL DROPLET) = 20.0
DDIN (INITIAL DROPLET DIAMETER OF LARGE DROPLET) = 600.0
FND (DESIGN ROTATIONAL SPEED) = 51120.0

DOMASS (DESIGN MASS FLOW RATE) = .3755

COMPRESSOR INLET TOTAL TEMPERATURE (GAS PHASE) = 518.70
COMPRESSOR INLET TOTAL PRESSURE = 2116.80

PREB (PERCENT OF WATER THAT REBOUND AFTER IMPINGEMENT) = 50.0 PERCENT

ROTOR SPEED = 51120.0 RPM

CORRECTED ROTOR SPEED = 51120.0 RPM (100.0 PER CENT OF DESIGN CORRECTED SPEED)
DESIGN POINT INFORMATION

COMPRESSOR INLET

TOTAL TEMPERATURE AT COMPRESSOR INLET = 518.7
TOTAL PRESSURE AT COMPRESSOR INLET = 2116.8
STATIC TEMPERATURE AT COMPRESSOR INLET = 456.2
STATIC PRESSURE AT COMPRESSOR INLET = 1813.7
STATIC DENSITY AT COMPRESSOR INLET = .0685
ACOUSTIC SPEED AT COMPRESSOR INLET = 1092.25
AXIAL VELOCITY AT COMPRESSOR INLET = 518.82
MACH NUMBER AT COMPRESSOR INLET = .475
STREAMTUBE AREA AT COMPRESSOR INLET = .01057
FLOW COEFFICIENT AT COMPRESSOR INLET = .5317
**DESIGN POINT INFORMATION**

### STAGE = 1

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**STAGE TOTAL PRESSURE RATIO AT DESIGN POINT = 1.15200**
**STAGE ADIABATIC EFFICIENCY AT DESIGN POINT = .95383**
**ROTOR TOTAL PRESSURE RATIO AT DESIGN POINT = 1.15400**
**ROTOR ADIABATIC EFFICIENCY AT DESIGN POINT = .96600**
**ROTOR TOTAL TEMPERATURE RATIO AT DESIGN POINT = 1.04323**
### DESIGN POINT INFORMATION

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**STAGE ADIABATIC EFFICIENCY AT DESIGN POINT = .93231**
**ROTOR TOTAL PRESSURE RATIO AT DESIGN POINT = 1.16500**
**ROTOR ADIABATIC EFFICIENCY AT DESIGN POINT = .96600**
**ROTOR TOTAL TEMPERATURE RATIO AT DESIGN POINT = 1.04618**
### DESIGN POINT INFORMATION

#### STAGE = 3

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**Stage Total Pressure Ratio at Design Point:** 1.21300

**Stage Adiabatic Efficiency at Design Point:** 0.33464

**Rotor Total Pressure Ratio at Design Point:** 1.32100

**Rotor Adiabatic Efficiency at Design Point:** 0.36800

**Rotor Total Temperature Ratio at Design Point:** 1.06062
### DESIGN POINT INFORMATION

#### Stage: 4

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Stage Total Pressure Ratio at Design Point: 1.22800
Stage Adiabatic Efficiency at Design Point: .93002
Rotor Total Pressure Ratio at Design Point: 1.23700
Rotor Adiabatic Efficiency at Design Point: .95500
Rotor Total Temperature Ratio at Design Point: 1.05481
********** DESIGN POINT INFORMATION **********

**** STAGE= 5 ****

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Stage Total Pressure Ratio at Design Point = 1.22100
Stage Adiabatic Efficiency at Design Point = .92580
Rotor Total Pressure Ratio at Design Point = 1.23000
Rotor Adiabatic Efficiency at Design Point = .96200
Rotor Total Temperature Ratio at Design Point = 1.06311
### DESIGN POINT INFORMATION

#### STAGE = 6

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**Stage Total Pressure Ratio at Design Point = 1.20800**

**Stage Adiabatic Efficiency at Design Point = 0.92365**

**Rotor Total Pressure Ratio at Design Point = 1.21500**

**Rotor Adiabatic Efficiency at Design Point = 0.33400**

**Rotor Total Temperature Ratio at Design Point = 1.05962**
**DESIGN POINT INFORMATION**

**OVERALL PERFORMANCE AT DESIGN POINT**

**COMPRESSOR INLET TOTAL TEMPERATURE** = 518.70

**COMPRESSOR INLET TOTAL PRESSURE** = 2116.80

**CORRECTED MASS FLOW RATE** = 3.168

**OVERALL TOTAL PRESSURE RATIO** = 2.9334

**OVERALL TOTAL TEMPERATURE RATIO** = 1.3886

**OVERALL ADIABATIC EFFICIENCY** = .9223

**OVERALL TEMPERATURE RISE** = 201.559

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260
INITIAL FLOW COEFFICIENT = .50000 (STAGE = 1)

STAGE TOTAL PRESSURE RATIO = 1.18052
STAGE TOTAL TEMPERATURE RATIO = 1.05118
STAGE ADIABATIC EFFICIENCY = .94398

STAGE FLOW COEFFICIENT = .500
AXIAL VELOCITY = 482.12
ROTOR SPEED = 964.04

STAGE TOTAL PRESSURE RATIO (ACTUAL) = 1.18052
STAGE TOTAL PRESSURE RATIO (IDEAL) = 1.19072
LOSS FACTOR IN ROTOR = 1.01779
LOSS FACTOR IN STATOR = .99767

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<td>.0690</td>
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<tr>
<td>2504.78</td>
<td>2064.66</td>
<td>545.2462</td>
<td>515.9463</td>
<td>.0750</td>
<td>.0750</td>
</tr>
<tr>
<td>2498.93</td>
<td>2151.05</td>
<td>545.2462</td>
<td>522.3760</td>
<td>.0772</td>
<td>.0772</td>
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<table>
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<tr>
<th>AXIAL VELOCITY</th>
<th>ABSOLUTE VELOCITY</th>
<th>RELATIVE VELOCITY</th>
<th>BLADE SPEED</th>
<th>TANG. COMP. ABS. Vel.</th>
<th>TANG. COMP. REL. Vel.</th>
<th>ACOUSTIC SPEED</th>
<th>ABSOLUTE MACH NUMBER</th>
<th>RELATIVE MACH NUMBER</th>
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<tbody>
<tr>
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<td>465.8891</td>
<td>480.6390</td>
<td>636.1474</td>
<td>136.1987</td>
<td>367.39 2443</td>
<td>1083.2243</td>
<td>.4580</td>
<td>.5327</td>
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<tr>
<td>465.8891</td>
<td>533.2170</td>
<td>524.1017</td>
<td>670.0514</td>
<td>367.2243</td>
<td>302.8271</td>
<td>1120.8102</td>
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<td>.4677</td>
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<th>FLOW AREA</th>
<th>ABSOLUTE FLOW ANGLE</th>
<th>RELATIVE FLOW ANGLE</th>
<th>INCIDENCE</th>
<th>DEVIATION</th>
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<tbody>
<tr>
<td>.5001</td>
<td>.0104</td>
<td>15.7748</td>
<td>46.0400</td>
<td>3.3200</td>
<td>7.2338</td>
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</table>

261
### INITIAL FLOW COEFFICIENT = 0.50000 (ISTAGE = 1)

**STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (JPERFM = 2)**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Total Pressure Ratio</th>
<th>Total Temperature Ratio</th>
<th>Adiabatic Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.18052</td>
<td>1.05118</td>
<td>0.94929</td>
</tr>
</tbody>
</table>

**STAGE INLET** **STAGE OUTLET** **STAGE OUTLET** **STAGE ADJUSTMENT**

| XU = | 0.0000 | 0.0000 | 0.0000 |
| XU' = | 0.0000 | 0.0000 | 0.0000 |
| XJ = | 0.0000 | 0.0000 | 0.0000 |
| XJ' = | 0.0000 | 0.0000 | 0.0000 |
| XAIR = | 1.00000 | 1.00000 | 1.00000 |
| XMETAN = | 0.0000 | 0.0000 | 0.0000 |
| XGAS = | 1.00000 | 1.00000 | 1.00000 |
| WMASS = | 0.0000 | 0.0000 | 0.0000 |
| WMH2O = | 0.0000 | 0.0000 | 0.0000 |
| WTMASS = | 0.0000 | 0.0000 | 0.0000 |
| AMASS = | 0.34491 | 0.34491 | 0.34491 |
| CHMASS = | 0.0000 | 0.0000 | 0.0000 |
| UMASS = | 0.0000 | 0.0000 | 0.0000 |
| GMASS = | 0.34491 | 0.34491 | 0.34491 |
| TMASS = | 0.34491 | 0.34491 | 0.34491 |
| WS = | 0.0000 | 0.0000 | 0.0000 |
| RHOA = | 0.07649 | 0.07500 | 0.07718 |
| RHOD = | 0.06504 | 0.07500 | 0.07718 |
| RHOG = | 0.06302 | 0.07500 | 0.07718 |
| TG = | 518.70000 | 545.24617 | 545.24617 |
| TH = | 513.70000 | 513.70000 | 513.70000 |
| TH' = | 513.70000 | 513.70000 | 513.70000 |
| P = | 2116.80000 | 2504.77686 | 2498.92898 |
| TB = | 671.40656 | 0.00000 | 679.62039 |
| TDEW = | 271.99506 | 273.35228 | 273.35228 |

---

262
### Initial Flow Coefficient: 0.50000 (Stage 2)

<table>
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<tr>
<th>Description</th>
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<tbody>
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</tr>
<tr>
<td>Stage Total Temperature Ratio</td>
<td>1.05273</td>
</tr>
<tr>
<td>Stage Adiabatic Efficiency</td>
<td>1.9538</td>
</tr>
<tr>
<td>Stage Flow Coefficient</td>
<td>0.499</td>
</tr>
<tr>
<td>Axial Velocity</td>
<td>480.65</td>
</tr>
<tr>
<td>Rotor Speed</td>
<td>964.04</td>
</tr>
<tr>
<td>Stage Total Pressure Ratio (Actual)</td>
<td>1.18150</td>
</tr>
<tr>
<td>Stage Total Pressure Ratio (Ideal)</td>
<td>1.19700</td>
</tr>
<tr>
<td>Loss Factor in Rotor</td>
<td>0.99305</td>
</tr>
<tr>
<td>Loss Factor in Stator</td>
<td>0.99331</td>
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</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tr>
<td>Total Pressure</td>
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</tr>
<tr>
<td>Static Pressure</td>
<td>2151.02</td>
</tr>
<tr>
<td>Total Temperature (Gas)</td>
<td>545.2462</td>
</tr>
<tr>
<td>Static Temperature (Gas)</td>
<td>522.3793</td>
</tr>
<tr>
<td>Static Density (Gas)</td>
<td>0.0772</td>
</tr>
<tr>
<td>Static Density (Mixure)</td>
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</tr>
<tr>
<td>Axial Velocity</td>
<td>480.6495</td>
</tr>
<tr>
<td>Absolute Velocity</td>
<td>524.1276</td>
</tr>
<tr>
<td>Relative Velocity</td>
<td>688.9633</td>
</tr>
<tr>
<td>Blade Speed</td>
<td>702.6172</td>
</tr>
<tr>
<td>Tang. Comp. of Abs. Vel.</td>
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<tr>
<td>Tang. Comp. of Rel. Vel.</td>
<td>493.6056</td>
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<tr>
<td>Acoustic Speed</td>
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</tr>
<tr>
<td>Absolute Mach Number</td>
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</tr>
<tr>
<td>Relative Mach Number</td>
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<td>Flow Coefficient</td>
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</tr>
<tr>
<td>Flow Area</td>
<td>0.0093</td>
</tr>
<tr>
<td>Absolute Flow Angle</td>
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</tr>
<tr>
<td>Relative Flow Angle</td>
<td>45.7619</td>
</tr>
<tr>
<td>Incidence</td>
<td>3.0219</td>
</tr>
<tr>
<td>Deviation</td>
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263
### INITIAL FLOW COEFFICIENT

**Stage Performance After Inter-Stage Adjustment (JPERF=2)**

<table>
<thead>
<tr>
<th><strong>Stage</strong></th>
<th><strong>Total Pressure Ratio</strong></th>
<th><strong>Total Temperature Ratio</strong></th>
<th><strong>Adiabatic Efficiency</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.18150</td>
<td>1.05273</td>
<td>.92538</td>
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<table>
<thead>
<tr>
<th><strong>Stage</strong></th>
<th><strong>Inlet</strong></th>
<th><strong>Outlet</strong></th>
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<tbody>
<tr>
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<td>0.0000</td>
</tr>
<tr>
<td><strong>Xw</strong></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Xair</strong></td>
<td>1.00000</td>
<td>1.00000</td>
</tr>
<tr>
<td><strong>Xmetan</strong></td>
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<td>0</td>
</tr>
<tr>
<td><strong>Xgas</strong></td>
<td>1.00000</td>
<td>1.00000</td>
</tr>
<tr>
<td><strong>Wmass</strong></td>
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<tr>
<td><strong>Wmass</strong></td>
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<tr>
<td><strong>Tmass</strong></td>
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</tr>
<tr>
<td><strong>Hmass</strong></td>
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<td>.34491</td>
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<tr>
<td><strong>Vmass</strong></td>
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<td>.00000</td>
</tr>
<tr>
<td><strong>Gmass</strong></td>
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<td>1.00000</td>
</tr>
<tr>
<td><strong>Wmass</strong></td>
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<tr>
<td><strong>Rhoa</strong></td>
<td>.06504</td>
<td>.08168</td>
</tr>
<tr>
<td><strong>Rhom</strong></td>
<td>.06504</td>
<td>.08168</td>
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<tr>
<td><strong>Rhog</strong></td>
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<td><strong>tc</strong></td>
<td>545.24817</td>
<td>573.99661</td>
</tr>
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<td><strong>Twh</strong></td>
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<td>513.7000</td>
</tr>
<tr>
<td><strong>Twh</strong></td>
<td>513.7000</td>
<td>0</td>
</tr>
<tr>
<td><strong>P</strong></td>
<td>2498.92898</td>
<td>2972.35955</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>679.62039</td>
<td>688.08016</td>
</tr>
<tr>
<td><strong>Tdeg</strong></td>
<td>273.35228</td>
<td>274.74555</td>
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### INITIAL FLOW COEFFICIENT = 0.50000 (STAGE = 3)

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<tr>
<td>Stage Total Temperature Ratio</td>
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</tr>
<tr>
<td>Stage Adiabatic Efficiency</td>
<td>0.92118</td>
</tr>
<tr>
<td>Axial Velocity</td>
<td>494.17</td>
</tr>
<tr>
<td>Rotor Speed</td>
<td>964.04</td>
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<td>Stage Total Pressure Ratio (Actual)</td>
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<tr>
<td>Stage Total Pressure Ratio (Ideal)</td>
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<tr>
<td>Total Pressure</td>
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<td>Total Pressure</td>
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<td>Static Pressure</td>
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<tr>
<td>Total Temperature (Gas)</td>
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<tr>
<td>Static Temperature (Gas)</td>
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</table>

265
### INTIAL FLOW COEFFICIENT = 0.50000 (ISTAGE=3)  

### STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (JPERFM=2)  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
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### Stage Inlet** **Stage Outlet** (BEFORE INTER-STAGE ADJUSTMENT)  

### Stage Outlet** (AFTER INTER-STAGE ADJUSTMENT)  

<table>
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<th>Value</th>
<th>Value</th>
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<td>XWT=</td>
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<tr>
<td>XMETAN=</td>
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<td>513.70000</td>
<td>513.70000</td>
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<tr>
<td>TWW=</td>
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<td>0</td>
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<tr>
<td>TB=</td>
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<td>TDEH=</td>
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</table>
INITIAL FLOW COEFFICIENT = .50000 (STAGE = 4)

<table>
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<tr>
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<th>Value</th>
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<tbody>
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<tr>
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<tr>
<td>Stage Flow Coefficient</td>
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<tr>
<td>Rotor Speed</td>
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</tr>
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<td>Stage Total Pressure Ratio (Ideal)</td>
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</tr>
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<tr>
<td>Loss Factor in Stator</td>
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</tr>
</tbody>
</table>

| Total Pressure (GAS)                           | 3630.55             |
| Static Pressure                                | 3166.66             |
| Total Temperature (GAS)                        | 611.8566            |
| Static Temperature (GAS)                       | 550.4681            |
| Static Density (GAS)                           | .1009               |
| Static Density (MIXTURE)                       | .1009               |
| Axial Velocity                                 | 494.0715            |
| Absolute Velocity                              | 530.6990            |
| Relative Velocity                              | 757.6978            |
| Blade Speed                                    | 768.1948            |
| Tang. Comp. of Abs. Vel.                       | 193.7390            |
| Tang. Comp. of Rel. Vel.                       | 574.4588            |
| Acoustic Speed                                 | 1188.6880           |
| Absolute Mach Number                           | .4465               |
| Relative Mach Number                           | .6374               |
| Flow Coefficient                               | .5125               |
| Flow Area                                      | .0069               |
| Absolute Flow Angle                            | 21.4115             |
| Relative Flow Angle                            | 49.3022             |
| Incidence                                      | 6.4522              |

| Absolute Mach Number                           | 45.4750             |
| Relative Mach Number                           | 23.9421             |
| Deviation                                      | 10.1821             |

| Absolute Mach Angle                            | 22.4163             |
| Relative Mach Angle                            | 47.50               |
| Deviation                                      | 10.6063             |

TOTAL PRESSURE: 3630.55 4556.82 4509.80
STATIC PRESSURE: 3166.66 3525.69 3957.68
TOTAL TEMPERATURE (GAS): 611.8566 654.3529 654.3529
STATIC TEMPERATURE (GAS): 550.4681 606.4910 630.6504
STATIC DENSITY (GAS): .1009 .1086 .1176
STATIC DENSITY (MIXTURE): .1009 .1086 .1176
AXIAL VELOCITY: 494.0715 522.8404 496.2018
ABSOLUTE VELOCITY: 530.6990 745.6155 536.7235
RELATIVE VELOCITY: 757.6978 572.0630
BLADE SPEED: 768.1948 763.7337 798.0839
TANG. COMP. OF ABS. VEL.: 193.7390 531.5829
TANG. COMP. OF REL. VEL.: 574.4588 232.1508
ACOUSTIC SPEED: 1188.6880 1230.0789 1230.5425
ABSOLUTE MACH NUMBER: .4465 .6169 .4362
RELATIVE MACH NUMBER: .6374 .4733
FLOW COEFFICIENT: .5125 .5423 .5147
FLOW AREA: .0069 .0061 .0059
ABSOLUTE FLOW ANGLE: 21.4115 45.4750 22.4163
RELATIVE FLOW ANGLE: 49.3022 23.9421
INCIDENCE: 6.4522 .4750
DEVIAATION: 10.1821 10.6063
**INITIAL FLOW COEFFICIENT** = 0.50000  (ISTAGE = 4)

**STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT** (JPERFM = 2)

**STAGE TOTAL PRESSURE RATIO** = 1.24219
**STAGE TOTAL TEMPERATURE RATIO** = 1.06878
**STAGE ADIABATIC EFFICIENCY** = 0.91298

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268
### Initial Flow Coefficient

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**INITIAL FLOW COEFFICIENT** = 0.50000 (ISTAGE=5)  

**STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (JPERFM=2)**

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STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (JPERFM=2)

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********** OVERALL PERFORMANCE **********

INITIAL FLOW COEFFICIENT = .50000
CORRECTED SPEED=51120.0  1.000 FRACTION OF DESIGN CORRECTED SPEED

INITIAL WATER CONTENT (SMALL DROPLET) = 0
INITIAL WATER CONTENT (LARGE DROPLET) = 0
INITIAL WATER CONTENT (TOTAL) = 0
INITIAL RELATIVE HUMIDITY = 0 PER CENT
INITIAL METHANE CONTENT = 0

COMPRESSOR INLET TOTAL TEMPERATURE = 518.70
COMPRESSOR INLET TOTAL PRESSURE = 2116.80
CORRECTED MASS FLOW RATE OF MIXTURE = 0.345 (2.910)
CORRECTED MASS FLOW RATE OF GAS PHASE = 0.345 (2.910)
OVERALL TOTAL PRESSURE RATIO = 3.2050
OVERALL TOTAL TEMPERATURE RATIO = 1.4336
OVERALL ADIABATIC EFFICIENCY = 0.9057
OVERALL TEMPERATURE RISE OF GAS PHASE = 224.894
A.5.2 Test Case Part II
### INPUT DATA

**NS (NUMBER OF STAGE) = 6**

**UNIT = ENGLISH UNIT**

**PERFORMANCE AT MEAN**

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FMF (FRACTION OF DESIGN CORRECTED SPEED) = 1.000
XIDIN (INITIAL WATER CONTENT OF SMALL DROPLET) = 0.040
XIDIN (INITIAL WATER CONTENT OF LARGE DROPLET) = 0
RHUMID (INITIAL RELATIVE HUMIDITY) = 0.00 PER CENT
XMCH (INITIAL METHANE CONTENT) = 0
TGC (COMPRESSOR INLET TOTAL TEMPERATURE OF GAS) = 518.70
TOH (COMPRESSOR INLET TEMPERATURE OF DROPLET) = 513.70
P0 (COMPRESSOR INLET TOTAL PRESSURE) = 2116.80
DIN (INITIAL DROPLET DIAMETER OF SMALL DROPLET) = 20.0
DDIN (INITIAL DROPLET DIAMETER OF LARGE DROPLET) = 600.0
FND (DESIGN ROTATIONAL SPEED) = 51120.0
DSMASS (DESIGN MASS FLOW RATE) = 0.3755
COMPRESSOR INLET TOTAL TEMPERATURE (GAS PHASE) = 518.70
COMPRESSOR INLET TOTAL PRESSURE = 2116.80
PREB (PERCENT OF WATER THAT REBOUND AFTER IMPINGEMENT) = 50.0 PERCENT
ROTOR SPEED = 51120.0 RPM
CORRECTED ROTOR SPEED = 51120.0 RPM (100.0 PER CENT OF DESIGN CORRECTED SPEED)
DESIGN POINT INFORMATION

COMPRESSOR INLET

TOTAL TEMPERATURE AT COMPRESSOR INLET = 518.70000
TOTAL PRESSURE AT COMPRESSOR INLET = 2116.80
STATIC TEMPERATURE AT COMPRESSOR INLET = 496.26109
STATIC PRESSURE AT COMPRESSOR INLET = 1813.73
STATIC DENSITY AT COMPRESSOR INLET = 0.06850

ACOUSTIC SPEED AT COMPRESSOR INLET = 1092.25914
AXIAL VELOCITY AT COMPRESSOR INLET = 518.81873
MACH NUMBER AT COMPRESSOR INLET = 0.47500
STREAMTUBE AREA AT COMPRESSOR INLET = 0.01057
FLOW COEFFICIENT AT COMPRESSOR INLET = 0.53817
### DESIGN POINT INFORMATION

#### STAGE= 1 ####

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Stage Total Pressure Ratio at Design Point = 1.15200
Stage Adiabatic Efficiency at Design Point = 0.95383
Rotor Total Pressure Ratio at Design Point = 1.15400
Rotor Adiabatic Efficiency at Design Point = 0.96800
Rotor Total Temperature Ratio at Design Point = 1.04328
### Design Point Information

#### Stage 2

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Stage Total Pressure Ratio at Design Point = 1.15900
Stage Adiabatic Efficiency at Design Point = .93231
Rotor Total Pressure Ratio at Design Point = 1.16500
Rotor Adiabatic Efficiency at Design Point = .96600
Rotor Total Temperature Ratio at Design Point = 1.04618

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### DESIGN POINT INFORMATION

#### STAGE: 3

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Stage Total Pressure Ratio at Design Point = 1.22800
Stage Adiabatic Efficiency at Design Point = 0.93002
Rotor Total Pressure Ratio at Design Point = 1.23700
Rotor Adiabatic Efficiency at Design Point = 0.96500
Rotor Total Temperature Ratio at Design Point = 1.06491
### DESIGN POINT INFORMATION

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- Stage Total Pressure Ratio at Design Point: 1.22100
- Stage Adiabatic Efficiency at Design Point: .92580
- Rotor Total Pressure Ratio at Design Point: 1.23000
- Rotor Adiabatic Efficiency at Design Point: .92620
- Rotor Total Temperature Ratio at Design Point: 1.06311
### DESIGN POINT INFORMATION

**Stage= 6**

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**Stage Total Pressure Ratio at Design Point=** 1.20800

**Stage Adiabatic Efficiency at Design Point=** .92365

**Rotor Total Pressure Ratio at Design Point=** 1.21500

**Rotor Adiabatic Efficiency at Design Point=** .95400

**Rotor Total Temperature Ratio at Design Point=** 1.05962
*************** DESIGN POINT INFORMATION ***************

********** OVERALL PERFORMANCE AT DESIGN POINT **********

COMPRESSOR INLET TOTAL TEMPERATURE = 518.70
COMPRESSOR INLET TOTAL PRESSURE = 2116.80
CORRECTED MASS FLOW RATE = 3.168
OVERALL TOTAL PRESSURE RATIO = 2.9334
OVERALL TOTAL TEMPERATURE RATIO = 1.3886
OVERALL ADIABATIC EFFICIENCY = .9223
OVERALL TEMPERATURE RISE = 201.559

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**INITIAL FLOW COEFFICIENT** = .50000 (STAGE= 1)

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**Stage**
- Total Pressure Ratio (Actual) = 1.17523
- Total Pressure Ratio (Ideal) = 1.18907
- Loss Factor in Rotor = 1.01550
- Loss Factor in Stator = .99678

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*ROTOR INLET*  |  *ROTOR OUTLET*  |  *STATOR OUTLET*  |
**INITIAL FLOW COEFFICIENT= .50000 (ISTAGE= 1)**

**STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (IPERFM=2)**

| **STAGE TOTAL PRESSURE RATIO** | 1.17523 |
| **STAGE TOTAL TEMPERATURE RATIO** | 1.05076 |
| **STAGE ADIABATIC EFFICIENCY** | .93059 |

**STAGE INLET** | **STAGE OUTLET** | (BEFORE INTER-STAGE ADJUSTMENT) | **STAGE OUTLET** | (AFTER INTER-STAGE ADJUSTMENT) |
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Stage Flow Coefficient = 0.501
Axial Velocity = 483.25
Rotary Speed = 964.04

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Loss Factor in Rotor = 0.99123
Loss Factor in Stator = 0.99193

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INITIAL FLOW COEFFICIENT = .50000 (ISTAGE = 2)

STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (JPERFM = 2)

STAGE TOTAL PRESSURE RATIO = 1.17581
STAGE TOTAL TEMPERATURE RATIO = 1.05225
STAGE ADIABATIC EFFICIENCY = .90625

**STAGE INLET**   **STAGE OUTLET**   **STAGE OUTLET**
(BEFORE INTER-STAGE ADJUStMENT) (AFTER INTER-STAGE ADJUSTMENT)

| XL | .00003 | .00003 | .00011 |
| XH | .03897 | .03897 | .03897 |
| XLH| .00000 | .00000 | .00000 |
| XHT| .03897 | .03897 | .03897 |
| XAIR| .96000 | .96000 | .96000 |
| XMET| 0 | 0 | 0 |
| XGAS| .96003 | .96003 | .96011 |
| WMASS| .01430 | .01430 | .01427 |
| WMASS| 0 | 0 | 0 |
| AMASS| .34340 | .34340 | .34340 |
| CHMSS| 0 | 0 | 0 |
| UMASS| .00001 | .00001 | .00004 |
| GMASS| .34341 | .34341 | .34344 |
| TMASS| .35771 | .35771 | .35771 |
| WS| .00004 | .00004 | .00011 |
| RHOA| .08555 | .08843 | .07670 |
| RHOM| .07160 | .08347 | .08918 |
| RHOG| .07543 | .08843 | .08563 |
| TG| 545.0235 | 573.50850 | 573.50651 |
| TH| 519.13056 | 524.60517 | 524.62018 |
| TW| 513.70000 | 0 | 513.70000 |
| TP| 2487.72825 | 2548.91263 | 2525.10631 |
| TB| 679.39541 | 0 | 687.60211 |
| TDEH| 395.40315 | 398.30836 | 418.76408 |

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**INITIAL FLOW COEFFICIENT** = 0.50000 (ISTAGE = 3)

**STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (JPERFM=2)**

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****STAGE INLET** | **STAGE OUTLET** | **STAGE OUTLET**
| (BEFORE INTER-STAGE ADJUSTMENT) | (AFTER INTER-STAGE ADJUSTMENT) |

| XU | 0.00011 | 0.00011 | 0.00023 |
| XW | 0.03989 | 0.03989 | 0.03977 |
| XH | 0 | 0 | 0 |
| XH2 | 0.03989 | 0.03989 | 0.03977 |
| XAIR | 0.96000 | 0.96000 | 0.96000 |
| XMETAN | 0 | 0 | 0 |
| XGAS | 0.96011 | 0.96011 | 0.96023 |
| WMASS | 0.01427 | 0.01427 | 0.01422 |
| HM & FUEL | 0.00004 | 0.00004 | 0.00008 |
| TM & FUEL | 0.34344 | 0.34344 | 0.34348 |
| CHMASS | 0.35771 | 0.35771 | 0.35771 |
| U | 0.00011 | 0.00011 | 0.00024 |
| RHOA | 0.09560 | 0.09133 | 0.09128 |
| RHOM | 0.07160 | 0.09511 | 0.10303 |
| RHOG | 0.08563 | 0.09132 | 0.08894 |
| TG | 573.50651 | 611.09874 | 611.09555 |
| TH | 524.62018 | 531.47995 | 531.49766 |
| TW | 513.70000 | 0 | 513.70000 |
| P | 2925.10631 | 3619.22732 | 3582.11448 |
| TB | 507.60211 | 0 | 698.15264 |
| TDEW | 415.76408 | 422.85381 | 437.94261 |

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**INITIAL FLOW COEFFICIENT = 0.50000 (STAGE = 4)**

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INITIAL FLOW COEFFICIENT= .50000 (ISTAGE= 4)

STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (PERFNM=2)

STAGE TOTAL PRESSURE RATIO= 1.23734
STAGE TOTAL TEMPERATURE RATIO= 1.06936
STAGE ADIABATIC EFFICIENCY= .90140
INITIAL FLOW COEFFICIENT= .50000 (STAGE= 5)

| Stage TOTAL PRESSURE RATIO= | 1.22960 |
| Stage TOTAL TEMPERATURE RATIO= | 1.06748 |
| Stage ADBIABATIC EFFICIENCY= | .89617 |
| Stage FLOW COEFFICIENT= | .525 |
| Axial VELOCITY= | 505.96 |
| Rotor SPEED= | 964.04 |
| Stage TOTAL PRESSURE RATIO ACTUAL= | 1.22960 |
| Stage TOTAL PRESSURE RATIO IDEAL= | 1.25805 |
| Loss FACTOR in ROTOR= | .98167 |
| Loss FACTOR in STATOR= | .98872 |

| TOTAL PRESSURE | 4432.28 | 5512.15 | 5449.36 |
| STATIC PRESSURE | 3650.09 | 4245.77 | 4766.53 |
| TOTAL TEMPERATURE(GAS) | 653.4829 | 697.5927 | 697.5927 |
| STATIC TEMPERATURE(GAS) | 627.0227 | 649.5072 | 672.5710 |
| STATIC DENSITY(GAS) | .1149 | .1225 | .1329 |
| STATIC DENSITY(MIXTURE) | .1116 | .1275 | .1383 |
| Axial VELOCITY | 505.9606 | 532.9952 | 505.9950 |
| Absolute VELOCITY | 545.4824 | 761.3362 | 549.5787 |
| Relative VELOCITY | 780.4500 | 532.9952 | 505.9950 |
| BLADE SPEED | 798.8833 | 787.8235 | 819.0509 |
| TANG. COMP. OF ABS. VELO. | 203.8501 | 544.4868 |
| TANG. COMP. OF REL. VELO. | 534.2338 | 243.3366 |
| ACUSTIC SPEED | 1202.9772 | 1244.6349 | 1245.1170 |
| Absolute MACH NUMBER | .4534 | .6227 | .4414 |
| Relative MACH NUMBER | .6488 | .4789 |
| Flow COEFFICIENT | .5248 | .5529 | .5249 |
| Flow AREA | .0059 | .0053 | .0051 |
| Absolute FLOW ANGLE | 21.9444 | 45.8111 | 22.9819 |
| Relative FLOW ANGLE | 49.5873 | 24.5368 |
| Incidence | 5.5873 | -6.6368 |
| Deviation | 10.2088 | 9.6619 |
INITIAL FLOW COEFFICIENT = 0.50000 (ISTAGE = 5) ***************

STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (JPERFM=2)

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* Rotor Inlet | Rotor Outlet | Stator Outlet

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Absolut Mach Number                             | .5149       |
Flow Area                                        | .0047       |
Absolute Flow Angle                              | 36.5240     |
Relative Flow Angle                              | 7.2440      |
Initial Flow Coefficient: .50000 (ISTAGE = 6)

Stage Performance After Inter-Stage Adjustment (JPERFM=2)

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<th>Total Temperature Ratio</th>
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**Stage Inlet** (Before Inter-Stage Adjustment) | **Stage Outlet** (After Inter-Stage Adjustment)

| XU=    | .00069               | .00069                  | .00105               |
| XW=    | .03331               | .03331                  | .03885               |
| X=     | 0                    | 0                       | 0                    |
| XAIR=  | .95000               | .95000                  | .95000               |
| XMETAM=| 0                    | 0                       | 0                    |
| XGRAS= | .96069               | .96069                  | .96105               |
| U=     | .01406               | .01406                  | .01393               |
| W=     | 0                    | 0                       | 0                    |
| W=     | .34340               | .34340                  | .34340               |
| VMAS=  | 0                    | 0                       | 0                    |
| GMAS=  | .34365               | .34365                  | .34377               |
| TMAS=  | .35771               | .35771                  | .35771               |
| S=     | .00072               | .00072                  | .00110               |
| RH0A=  | .13044               | .14172                  | .13434               |
| RH0M=  | .07160               | .14744                  | .15538               |
| RH0G=  | .13303               | .14165                  | .14935               |
| TG=    | 697.57655            | 741.77019               | 741.76245            |
| TH=    | 545.89207            | 552.93791               | 552.93194            |
| TH=    | 513.70000            | 513.70000               | 513.70000            |
| P=     | 5449.95512           | 6683.24452              | 6619.78326           |
| TB=    | 724.03629            | 735.93466               | 735.93466            |
| TDEW=  | 463.59244            | 468.68226               | 475.11464            |

296
OVERALL PERFORMANCE

INITIAL FLOW COEFFICIENT = .5000

CORRECTED SPEED = 5112.0

1.000 FRACTION OF DESIGN CORRECTED SPEED

INITIAL WATER CONTENT (SMALL DROPLET) = .040

INITIAL WATER CONTENT (LARGE DROPLET) = 0

INITIAL WATER CONTENT (TOTAL) = .040

INITIAL RELATIVE HUMIDITY = 0 PER CENT

INITIAL METHANE CONTENT = 0

COMPRESSOR INLET TOTAL TEMPERATURE = 518.70

COMPRESSOR INLET TOTAL PRESSURE = 2116.80

CORRECTED MASS FLOW RATE OF MIXTURE = .358 (3.018)

CORRECTED MASS FLOW RATE OF GAS PHASE = .343 (2.897)

OVERALL TOTAL PRESSURE RATIO = 3.1273

OVERALL TOTAL TEMPERATURE RATIO = 1.4300

OVERALL ADIABATIC EFFICIENCY = .8905

OVERALL TEMPERATURE RISE OF GAS PHASE = 223.062
A.5.3 Test Case Part III
**INPUT DATA**

- **NS** (NUMBER OF STAGES) = 6
- **UNIT** = ENGLISH UNIT
- **IPERM** = 2
- **PERFORMANCE AT MEAN**

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FNF (FRACTION OF DESIGN CORRECTED SPEED) = 1.000

XDN (INITIAL WATER CONTENT OF SMALL DROPLET) = 0
XDDN (INITIAL WATER CONTENT OF LARGE DROPLET) = 0.040
XHM (INITIAL RELATIVE HUMIDITY) = 0.00 PER CENT
XCH4 (INITIAL METHANE CONTENT) = 0

TGC (COMPRESSOR INLET TOTAL TEMPERATURE OF GAS) = 518.70
TOW (COMPRESSOR INLET TEMPERATURE OF DROPLET) = 513.70
P0 (COMPRESSOR INLET TOTAL PRESSURE) = 2116.80

DIN (INITIAL DROPLET DIAMETER OF SMALL DROPLET) = 20.0
DDIN (INITIAL DROPLET DIAMETER OF LARGE DROPLET) = 600.0

FND (DESIGN ROTATIONAL SPEED) = 51120.0

DSMASS (DESIGN MASS FLOW RATE) = 0.3755

COMPRESSOR INLET TOTAL TEMPERATURE (GAS PHASE) = 518.70
COMPRESSOR INLET TOTAL PRESSURE = 2116.80

PREB (PERCENT OF WATER THAT REBOUND AFTER IMPINGEMENT) = 50.0 PERCENT

ROTOR SPEED = 51120.0 RPM
CORRECTED ROTOR SPEED = 51120.0 RPM (100.0 PER CENT OF DESIGN CORRECTED SPEED)
*************** DESIGN POINT INFORMATION ***************

****** COMPRESSOR INLET ******

TOTAL TEMPERATURE AT COMPRESSOR INLET = 518.70000
TOTAL PRESSURE AT COMPRESSOR INLET = 2116.80
STATIC TEMPERATURE AT COMPRESSOR INLET = 456.28108
STATIC PRESSURE AT COMPRESSOR INLET = 1813.73
STATIC DENSITY AT COMPRESSOR INLET = 0.06850

ACOUSTIC SPEED AT COMPRESSOR INLET = 1092.25914
AXIAL VELOCITY AT COMPRESSOR INLET = 518.81873
MACH NUMBER AT COMPRESSOR INLET = 0.47500
STREAMTUBE AREA AT COMPRESSOR INLET = 0.01057
FLOW COEFFICIENT AT COMPRESSOR INLET = 0.53817
### DESIGN POINT INFORMATION

#### STAGE= 1

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### DESIGN POINT INFORMATION

#### STAGE = 2

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**Stage Total Pressure Ratio at Design Point** = 1.15900

**Stage Adiabatic Efficiency at Design Point** = .93231

**Rotor Total Pressure Ratio at Design Point** = 1.12500

**Rotor Adiabatic Efficiency at Design Point** = .96600

**Rotor Total Temperature Ratio at Design Point** = 1.04618
### DESIGN POINT INFORMATION

#### STAGE = 3

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| STAGE TOTAL PRESSURE RATIO AT DESIGN POINT | 1.21300 |
| STAGE ADIABATIC EFFICIENCY AT DESIGN POINT | 0.53464 |
| ROTOR TOTAL PRESSURE RATIO AT DESIGN POINT | 1.22100 |
| ROTOR ADIABATIC EFFICIENCY AT DESIGN POINT | 0.96800 |
| ROTOR TOTAL TEMPERATURE RATIO AT DESIGN POINT | 1.06062 |
## DESIGN POINT INFORMATION

### Stage: 4

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Stage Total Pressure Ratio at Design Point = 1.22800
Stage Adiabatic Efficiency at Design Point = .93002
Rotor Total Pressure Ratio at Design Point = 1.23700
Tor Adiabatic Efficiency at Design Point = .96500
Rotor Total Temperature Ratio at Design Point = 1.06481
### Stage 3 Information

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Stage Total Pressure Ratio at Design Point: 1.22100
Stage Adiabatic Efficiency at Design Point: 0.92580
Rotor Total Pressure Ratio at Design Point: 1.23000
Rotor Adiabatic Efficiency at Design Point: 0.96200
Rotor Total Temperature Ratio at Design Point: 1.06311
### DESIGN POINT INFORMATION

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Stage Total Pressure Ratio at Design Point: 1.20800
Stage Adiabatic Efficiency at Design Point: 0.92365
Rotor Total Pressure Ratio at Design Point: 1.21500
Rotor Adiabatic Efficiency at Design Point: 0.95400
Rotor Total Temperature Ratio at Design Point: 1.05962
### DESIGN POINT INFORMATION

**OVERALL PERFORMANCE AT DESIGN POINT**

- **Compressor Inlet Total Temperature**: 518.70
- **Compressor Inlet Total Pressure**: 2116.80
- **Corrected Mass Flow Rate**: 3.168
- **Overall Total Pressure Ratio**: 2.9334
- **Overall Total Temperature Ratio**: 1.3886
- **Overall Adiabatic Efficiency**: 0.9223
- **Overall Temperature Rise**: 201.559

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**INITIAL FLOW COEFFICIENT** - 0.50000 (STAGE = 1)

| Stage Total Pressure Ratio | 1.16790 |
| Stage Total Temperature Ratio | 1.05044 |
| Stage Adiabatic Efficiency | 0.89332 |
| Stage Flow Coefficient | 0.500 |
| Axial Velocity | 482.10 |
| Rotor Speed | 964.04 |
| Stage Total Pressure Ratio (Actual) | 1.16790 |
| Stage Total Pressure Ratio (Ideal) | 1.18781 |
| Loss Factor in Rotor | 1.01167 |
| Loss Factor in Stator | 0.99536 |

| TOTAL PRESSURE | 2116.80 | 2453.73 | 2472.21 |
| STATIC PRESSURE | 1822.02 | 2027.51 | 2105.98 |
| TOTAL TEMPERATURE (GAS) | 518.7000 | 544.8657 | 544.8657 |
| STATIC TEMPERATURE (GAS) | 498.5285 | 515.3151 | 521.3802 |
| STATIC DENSITY (GAS) | 0.0687 | 0.0737 | 0.0757 |
| STATIC DENSITY (MIXTURE) | 0.0716 | 0.0768 | 0.0789 |
| AXIAL VELOCITY | 482.0985 | 471.7651 | 487.8474 |
| ABSOLUTE VELOCITY | 500.9664 | 595.7508 | 530.9822 |
| RELATIVE VELOCITY | 634.5315 | 562.4474 |
| BLADE SPEED | 636.1474 | 670.0514 | 702.6172 |
| TANG. COMP. OF ABS. VEL. | 136.1924 | 363.8085 |
| TANG. COMP. OF REL. VEL. | 499.9850 | 305.2429 |
| ACOUSTIC SPEED | 1070.9380 | 1050.5707 | 1096.9841 |
| ABSOLUTE MACH NUMBER | 0.4678 | 0.5463 | 0.4840 |
| RELATIVE MACH NUMBER | 0.6485 | 0.5157 |
| FLOW COEFFICIENT | 0.5001 | 0.4894 | 0.5060 |
| FLOW AREA | 0.0104 | 0.0099 | 0.0093 |
| ABSOLUTE FLOW ANGLE | 15.7749 | 37.6381 | 23.2615 |
| RELATIVE FLOW ANGLE | 48.0417 | 32.9883 |
| INCIDENCE | 3.3217 | 2.4881 |
| DEVIATION | 1.1993 | 11.0715 |

*Rotor Inlet* *Rotor Outlet* *Stator Outlet*
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<th><strong>STAGE OUTLET</strong> (BEFORE INTER-STAGE ADJUSTMENT)</th>
<th><strong>STAGE OUTLET</strong> (AFTER INTER-STAGE ADJUSTMENT)</th>
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<td>XU= 0.0000</td>
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INITIAL FLOW COEFFICIENT= .50000 (STAGE= 2 )

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<th>Adiabatic Efficiency</th>
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<tr>
<td>St 2</td>
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| Axial Velocity | 486.86 |
| Rotor Speed    | 964.04 |

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<th>Total Pressure Ratio (Actual)</th>
<th>Total Pressure Ratio (Ideal)</th>
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</thead>
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<tr>
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<td>1.05175</td>
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<tr>
<td>St 2</td>
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<td>1.05175</td>
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| Loss Factor in Rotor | .99882 |
| Loss Factor in Stator| .99882 |

**Stage Data**

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<th>Value 3</th>
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<td>Deviation</td>
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### Initial Flow Coefficient

- Initial Flow Coefficient: 0.50000 (Istage = 2)

### Stage Performance After Inter-Stage Adjustment

- **Stage Total Pressure Ratio**: 1.16781
- **Stage Total Temperature Ratio**: 1.05175
- **Stage Adiabatic Efficiency**: 0.87561

#### Stage Inlet and Outlet Values

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>After Inter-Stage Adjustment</th>
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<td>XUH</td>
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<td>0.02199</td>
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#### Mass Flow Rates

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<td>Condensate</td>
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**Notes:**

- The table above summarizes the stage performance after inter-stage adjustment, including total pressure and temperature ratios, adiabatic efficiency, and mass flow rates for various components.
- The values are rounded to the nearest decimal place for clarity.

---

**Additional Details:**

- **XU, XH, XUH, XHET, XAIR, XMET, WMASS, CHMASS, WMASS, and WMASS** represent various flow rates or mass ratios.
- **XUW, XUW, and XUW** indicate specific flow rates or mass flow rates.
- **PG** stands for specific pressure or mass flow rates.
- **TDEW** represents the dew point temperature.
INITIAL FLOW COEFFICIENT - 0.50000 (STAGE = 3)

<table>
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<th>Value</th>
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<td>Stage Total Temperature Ratio</td>
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<td>Stage Adiabatic Efficiency</td>
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<td>Stage Flow Coefficient</td>
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<table>
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313
**INITIAL FLOW COEFFICIENT= .50000** (ISTAGE= 3)

STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT(JPERF=3)

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314
### INITIAL FLOW COEFFICIENT: 0.50000 (STAGE 4)

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<table>
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**Note:** The values in the table are representative of the stage performance parameters.
INITIAL FLOW COEFFICIENT = 0.50000 (ISTAGE = 4)

STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (JPERF = 2)

STAGE TOTAL PRESSURE RATIO = 1.23657
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STAGE ADIABATIC EFFICIENCY = 0.90822

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**Notes:**
- Stage Total Temperature Ratio and Stage Adiabatic Efficiency are also listed.
- The table includes various pressure, temperature, density, and velocity values for different stages.
- Flow coefficients and area values are also provided.
- The values for flow angle and deviation are given in degrees.
*************** INITIAL FLOW COEFFICIENT = .50000 (ISTAGE=5) ***************

STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (JPERF=2)

STAGE TOTAL PRESSURE RATIO = 1.22899
STAGE TOTAL TEMPERATURE RATIO = 1.06664
STAGE ADIABATIC EFFICIENCY = .90448

**STAGE INLET** **STAGE OUTLET** **STAGE OUTLET**
(BEFORE INTER-
STAGE ADJUST-
MENT) (AFTER INTER-
STAGE ADJUST-
MENT)

| XU   | .00248 | .00248 | .00599 |
| XH   | .03307 | .03307 | .03080 |
| XW   | .00445 | .00445 | .00599 |
| XNT  | .03752 | .03752 | .03080 |
| XNAT | .96000 | .96000 | .96360 |
| XMET| 0 0 0 | 0 0 0 | 0 0 0 |
| XGAS | .96248 | .96248 | .96248 |
| WMAS| .01183 | .01183 | .01099 |
| WMAS | .00159 | .00159 | .01099 |
| WMAS | .01342 | .01342 | .01099 |
| AMAS | .34340 | .34340 | .34340 |
| CMASS | 0 0 0 | 0 0 0 | 0 0 0 |
| VMAS | .00089 | .00089 | .00199 |
| GMAS | .34429 | .34429 | .34539 |
| TMAS | .35771 | .35771 | .35637 |
| US  | .00259 | .00259 | .00580 |
| RHDA | .12487 | .12017 | .11734 |
| RHDA | .07160 | .12487 | .13362 |
| RHDA | .11218 | .11598 | .12671 |
| TG  | 652.14134 | 695.67091 | 695.59980 |
| TH  | 533.59527 | 540.88803 | 541.37489 |
| TH  | 513.70137 | 513.70036 | 513.70155 |
| P   | 4344.79698 | 5395.45042 | 5339.72028 |
| TB  | 708.50566 | 0 0 0 | 722.00682 |
| TDEH| 498.37453 | 496.93587 | 520.46557 |
INITIAL FLOW COEFFICIENT = 0.50000 (STAGE = 6)

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INITIAL FLOW COEFFICIENT = .50000 (STAGE=6)  

STAGE PERFORMANCE AFTER INTER-STAGE ADJUSTMENT (JPERFM=2)

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********** OVERALL PERFORMANCE **********

INITIAL FLOW COEFFICIENT = 0.50000

CORRECTED SPEED = 51120.0  1.000 FRACTION OF DESIGN CORRECTED SPEED

INITIAL WATER CONTENT (SMALL DROPLET) = 0
INITIAL WATER CONTENT (LARGE DROPLET) = 0.040
INITIAL WATER CONTENT (TOTAL) = 0.040
INITIAL RELATIVE HUMIDITY = 0 PER CENT
INITIAL METHANE CONTENT = 0

COMPRESSOR INLET TOTAL TEMPERATURE = 518.70
COMPRESSOR INLET TOTAL PRESSURE = 2116.80
CORRECTED MASS FLOW RATE OF MIXTURE = 0.358 (3.018)
CORRECTED MASS FLOW RATE OF GAS PHASE = 0.343 (2.897)
OVERALL TOTAL PRESSURE RATIO = 3.0618
OVERALL TOTAL TEMPERATURE RATIO = 1.4244
OVERALL ADIABATIC EFFICIENCY = 0.8805
OVERALL TEMPERATURE RISE OF GAS PHASE = 220.159


LIST OF REFERENCES


(19) Keller, H., Erosionskorrosion on Heissdampfturbinen VGB Kraftwekstechnik, 1974, Heft 5.


