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Transient Compressible Flow in a Piping Network: A Solution Method and Computer Simulation

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PREFACE

This report documents work performed under Independent Research and Independent Exploratory Development (IR/IED) Project No. A43115, "Compressible Pipe Flow Simulation." Principal investigator was Paul J. Lefebvre (Code 3711). Associate investigator was Richard F. Hubbell (Code 3711). Technical reviewer was William G. Fennell (Code 3634).

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A general method of calculating the transient state of compressible fluid flow through complex piping networks has been developed and a computer program implementing this method has been written. This report presents the theory and logic upon which the solution method and program are based. It serves also as a basic introduction to the program, which is written for persons having minimal knowledge of compressible flow theory.

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INTRODUCTION

This report describes work conducted under the NUSC Independent Research and Independent Exploratory Development project titled "Transient Compressible Pipe Flow Simulation." The main objectives of this project were to develop numerical techniques for calculating transient compressible flow of a fluid through complex piping networks and to create a user-oriented computer simulation sufficiently general to be applicable to a wide variety of networks. The end result of this effort is a computer program called COMP, which has been implemented at the Naval Underwater Systems Center on a Digital Equipment Corporation VAX 11/780 computer.

Several simulations for adiabatic flow of compressible gas in relatively complex piping networks have been developed over the past 20 years (see references 1 through 5). Each, however, was written for a specific application and consequently has serious drawbacks when applied to other networks. Specifically, the simulations are not user-oriented (making it difficult to define and set up the network), are not applicable to choked flow across throttling devices such as nozzles and valves, and are not readily applicable to transient flow where a combination of conditions (e.g., constant pressure, constant volume, or variable volume) may exist at supply and receiving tanks.

The simulation described in this report overcomes these drawbacks. In addition, it provides a new technique for rapid convergence of mass flow rate distributions at junctions common to two or more pipe lines, can account for any ideal gas, and employs numerical techniques for all calculations requiring iteration or integration. It can be expanded to accommodate practically any piping network.

The simulation assumes adiabatic flow in each line. It accounts for irreversibilities encountered in throttling devices and for frictional effects in the pipe and fittings by treating them as equivalent pipe lengths. Figure 1 shows the network used in the simulation. Circled numbers in the figure indicate tanks, uncircled numbers indicate pipe sections, and circled letters indicate junctions. Pipe sections connect two junctions or a tank and a junction. Each pipe section can consist of up to 10 pipe lengths arranged in series. Throttling devices can be substituted for pipe lengths, but cannot be the first or last lengths in a section.

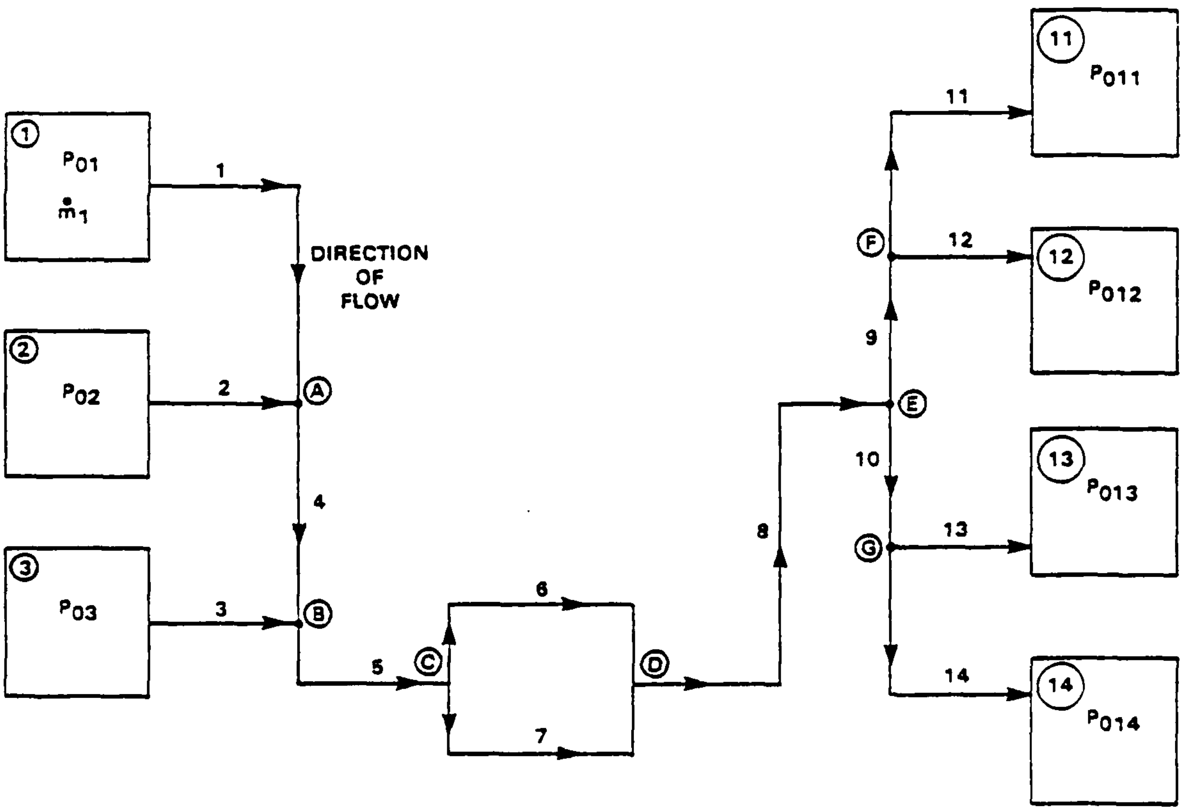

Figure 1. Compressible Flow Network

DISCUSSION

THEORY

The general approach used here in solving the transient compressible flow problem in a piping network is similar to that used in reference 1. Namely, adiabatic frictional flow is assumed to exist in each line of the network and the system's mass flow rate is determined by balancing mass flow rate and stagnation pressure at a single point (called the common point), which is subject to the total system mass flow rate. For the initial time increment in this transient flow problem, calculations first proceed in a forward direction from the most remote supply tank to the common point, and then in a backward direction from the most remote receiving tank to the common point. Stagnation pressure values at the common point as calculated by these forward and backward computations or "passes" are then compared. If they are not approximately equal, the mass flow rate calculations undergo repeated iterations until they balance. Once convergence of stagnation pressures at the common point occurs, the simulation employs a Runge-Kutta integration scheme to set up tank conditions for the beginning of the next time increment, whereupon the calculation process for stagnation pressures at the common point is repeated.

The equations used to calculate compressible adiabatic flow are taken from reference 6 and are not repeated here. The convergence scheme, however, was developed along with the simulation itself. The scheme is programmed as one of the simulation's main subroutines (subroutine RATIO) and is discussed along with other subroutines later.

ASSUMPTIONS

Assumptions made in conducting this analysis are as follows:

1. Flow is one-dimensional, quasi-steady, and adiabatic.
2. Ratio of specific heats is constant.
3. Ideal fluid compressibility factor, Z, is constant and equal to unity.
4. Friction factor, f, for any length of pipe is equal to the average of the inlet and outlet steady-state friction factors.
5. Minor losses due to elbows, reducers, etc., are introduced as equivalent pipe lengths.
6. No reverse flow exists in any line.
7. Isentropic stagnation pressures are balanced at each junction of two or more pipe lines.
8. Isothermal thermodynamic processes exist in each tank.

STRATEGY

The junctions between pipe sections are assumed to be isentropic, since any frictional effects due to the junctions may be compensated for by adding equivalent pipe lengths to the network. The isentropic condition at junctions forces the conclusion that there must be a single common stagnation pressure for all pipe lengths common to a junction. This assumption is critical to the analysis because it leads to the condition that the stagnation pressure is the property to be iterated upon at each junction in order to determine mass flow rate distribution.

One important exception to this condition is evident when throttling or choking occurs in a pipe terminating at a junction. The stagnation pressure calculated at the end of this pipe may be greater than the junction stagnation pressure, with the pressure difference being lost in the choked pipe as the flow enters the junction.

The overall approach to calculations in the forward direction is to assume a mass flow rate in the most remote and always present supply tank. This is tank 1 and mass flow rate $\dot{m}_1$ in figure 1. Throughout the transient there must be some absolute flow from this tank since it controls the overall calculation process. Calculations proceed to the first junction (junction A in figure 1), where a stagnation pressure at the end of pipe section 1 is calculated. The program next assumes a mass flow rate from tank 2 into pipe section 2 ($\dot{m}_2$), and calculates a stagnation pressure at junction A from section 2. If this stagnation pressure is within 1 psi of that calculated from section 1, calculations proceed to section 4; if it is not, adjustment is made to $\dot{m}_2$, via the convergence scheme (subroutine RATIO), while $\dot{m}_1$ is held at the initial value. As soon as agreement is reached (usually 2 to 5 iterations on $\dot{m}_2$), an arithmetic average of stagnation pressures at junction A is made and calculations continue.

Mass flow rate $\dot{m}_4$ is then taken to be the sum of $\dot{m}_1$ and $\dot{m}_2$. The starting pressure for section 4 is taken as the junction stagnation pressure obtained from sections 1 and 2. A stagnation pressure at junction B from section 4 is then calculated. The iterative procedure used to calculate the tank 2 flow is next employed again for tank 3 to obtain a value for $\dot{m}_3$ and a stagnation pressure at junction B. This completes the forward pass, since junction B is the common point where the forward and backward calculations meet.

The backward pass begins at the receiving tanks and proceeds toward the common point, junction B. It is assumed that whatever mass flowed into the system from the supply tanks will flow out of the system into the receiving tanks during any particular time step. To ensure that this condition is met, the program takes a percentage of the mass flowing into junction B from the forward calculations, and uses that as the mass flow in section 9. The remainder goes to section 10. The flow in section 9 is then divided between sections 11 and 12 (initially 50 percent in each). Calculations proceed to determine the stagnation pressure at junction F that would be required to produce that estimate of $\dot{m}_{11}$. Stagnation pressure at junction F from section 12 is calculated next and compared to the pressure from section 11. If the two do not agree, a mass flow rate adjustment is again made via subroutine RATIO.

Once agreement is reached, $\dot{m}_9$ is used to back-calculate the stagnation pressure required at junction E for a flow rate of $\dot{m}_9$. The program proceeds identically in sections 13 and 14 to junction E. If the stagnation pressure at junction E from section 9 does not match the one from section 10 within limits set into the program (presently 1 psi), then subroutine RATIO adjusts $\dot{m}_9$ and $\dot{m}_{10}$ until agreement is reached. The correct $\dot{m}_9$ and $\dot{m}_{10}$ values are rapidly obtained, resulting in a calculated stagnation pressure at junction E from the backward calculation. Note that if $\dot{m}_9$ and $\dot{m}_{11}$ are adjusted, then $\dot{m}_{11}$ through $\dot{m}_{14}$ must also be adjusted and all backward pass calculations repeated from the tanks.

Calculations proceed to the beginning of section 8 where stagnation pressure at junction D is obtained. The flow then splits into the parallel branches of sections 6 and 7. Under the initial assumption that the flow is equally split between sections 6 and 7, the pressure at junction C based on each section's contribution is then determined.

If agreement is achieved within the set limits of 1 psi, the parallel branch calculations are complete and the simulation calculates the conditions for section 5. If there is no agreement, subroutine RATIO adjusts the percentage of flow going to section 6 (which then gives a new flow rate in section 7 since $\dot{m}_7 = \dot{m}_5 - \dot{m}_6$) until convergence is achieved. Stagnation pressure at junction B is then calculated. This completes the backward pass, since junction B is the common point.

The overall convergence scheme of subroutine RATIO is once again accessed. It now compares the stagnation pressure at junction B from the forward pass with stagnation pressure from the backward pass. If they match (within 1 psi) the network is solved for that time step. If they do not match, an adjustment to $\dot{m}_1$ is made via subroutine RATIO and the forward and backward pass calculations are again repeated with the new value for $\dot{m}_1$. Iterations on $\dot{m}_1$ continue until stagnation pressure values at common point B as calculated from the forward and backward passes agree. At that time, all distributed mass flow rates and junction pressure values are correct, values for that particular time increment are output to the output file, and calculations for subsequent time increments begin. Initial conditions used for the subsequent time increment are determined by a Runge-Kutta integration.

RUNGE-KUTTA INTEGRATION SCHEME

The accuracy of the program in predicting the transient behavior of the network depends, in part, upon the technique selected to update the conditions within the supply and receiving tanks. The experience of the authors with different numerical integration schemes led to the selection of a fourth-order, Runge-Kutta technique, which is ideally suited to this particular application.

The technique is straightforward. The initial condition of each tank with respect to volume, temperature, pressure, and type of gas being used is known. The initial mass of gas contained within each tank is first calculated by the perfect gas law, the forward and backward passes are run, and the overall convergence criteria are applied at the common point. Once convergence at the common point is achieved, the mass flow rate from (or into) each tank, as well as that through all the pipes, and across each junction is known. With the initial mass within a tank and mass flow rate known, it is possible to calculate a new mass within the tank by means of a Runge-Kutta integration. Figure 2 illustrates this concept. Once the new mass is found, the perfect gas law is once again used to obtain new pressures under the assumption of isothermal tank processes. Having new pressures at the beginning of the next time increment allows the calculation process to begin again.

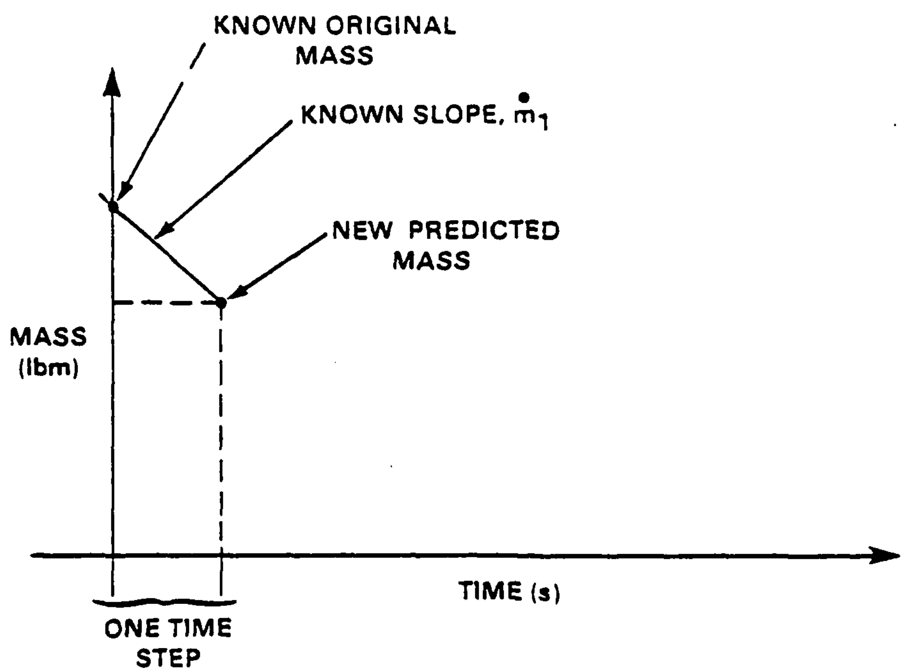

Figure 2. Runge-Kutta Integration Scheme

In the event that the tank has a variable volume, the user may employ a differential equation to describe the volume rate of change of the tank with respect to time. The differential equation can be non-linear, but must be ordinary. In running the simulation, the user inserts the equations into the FORTRAN main program in a section clearly labeled with comment statements. An example would be the following equation:

dV2/dt = 2 x Time x Time + 32.0

which would be inserted into the program as

```
F(2) = 2 * TIME * TIME + 32.0
```

in the section marked for tank 2. It would also be necessary to initialize the volume of tank 2 in this example at time = 0. The FORTRAN statement is Y(2) = 32.0, which would indicate an initial volume of 32 cubic feet.

CONVERGENCE TECHNIQUE

The assumptions that the flow is adiabatic and frictional provide no explicit equation for pressure drop in terms of a mass flow rate through a pipe, as would be the case for isothermal pipe flow. Instead, the problem involves a set of very non-linear algebraic equations that must be solved simultaneously. The problem experienced when the wrong mass flow rate is initially selected is that the stagnation pressures do not match at the junctions. For example, consider section 2, with $\dot{m}_2$ flowing to junction A. At junction A a value for stagnation pressure from section 1 has been obtained and it is now necessary to arrive at the correct value of $\dot{m}_2$ in order to have the junction A stagnation pressure from section 2 match the pressure from section 1. In short $\dot{m}_2$ must be made to converge to the correct value. Since the equations being used to calculate junction pressures are non-linear, a technique had to be devised to cause $\dot{m}_2$ to converge rapidly. Indeed, one of the main contributions of this study is the method that was developed to cause the mass flow rates to converge. The method is extremely fast and general. For example, with an initial estimate of $\dot{m}_2$ of 0.1 lbm/s when the actual converged value should be 100.0 lbm/s, the method used here will yield the correct value in only six iterations.

The method is as follows: an initial value of $\dot{m}_2$ is estimated from which a stagnation pressure at junction A is calculated. If the estimate does not result in convergence it must be adjusted and the procedure repeated. If the stagnation pressures from sections 1 and 2 are far apart at junction A, then a relatively large adjustment must be made, and the direction in which the adjustment must be made is known. If the value calculated for section 2 was too low at the junction, then $\dot{m}_2$ must be reduced so there is less pressure drop through section 2, thus increasing the section 2 stagnation pressure value at the junction. If the calculation for section 2 was too high at the junction, then $\dot{m}_2$ must be increased in order to lower the section 2 pressure value. It is not desirable to simply add or subtract a fixed amount to $\dot{m}_2$ because it is not possible to know ahead of time how large $\dot{m}_2$ should be.

For efficient convergence, a method was developed that is sensitive not only to the size (and sign) of the pressure difference at junction A, but to the size of $\dot{m}_2$ as well. The method uses the exponential function:

$$y_{new} = (y_{old}) \exp (\text{Constant} * x)$$

where $y = \dot{m}_2$ and x = junction A stagnation pressure from section 2 minus the stagnation pressure from section 1.

The choice of constant will depend on how quickly convergence is desired and how sensitive x is to small changes in y. The constant value in the simulation as it currently exists is good for most situations, but may have to be changed for very small pipe diameters. Tables 1a and 1b illustrate convergence for two very different size y-values when the constant equals 0.00005.

Table 1a. Small y-Value Convergence

x	y_{old}		y_{new}
+ 1000.0	0.1		0.1051271
+ 50.0	0.1051271		0.1053903
- 10.0	0.1053903		0.1053376
+ 1.5	0.1053376		0.1053455
- 0.2	0.1053455	Convergence	0.1053444

Table 1b. Large y-Value Convergence

x	y_{old}		y_{new}
+ 1005.0	85.0		89.380385
+ 500.0	89.380385		91.643061
+ 300.0	91.643061		93.028068
+ 60.0	93.028068		93.307571
- 5.0	93.307571		93.284247
+ 0.2	93.284247	Convergence	93.285180

This convergence method is also used to adjust the ratio of mass flow rates at a junction having two pipe sections leaving or entering from it.

At junction C, for example, RATIO(6) can be defined as $\dot{m}_6/\dot{m}_{total}$. Then, by adjusting RATIO(6) using two equations (see figure 3) it is possible to split the flow by the appropriate amount:

$$a = RATIO(6)_{new}$$
$$= RATIO(6)_{old} \exp(C_1 x) \qquad \text{(for } C_1 > 0 \text{ and } x > 0)$$
$$= 1 - \exp(-C_2 x) + RATIO(6)_{old} * \exp(-C_2 x) \qquad \text{(for } C_2 > 0 \text{ and } x < 0).$$

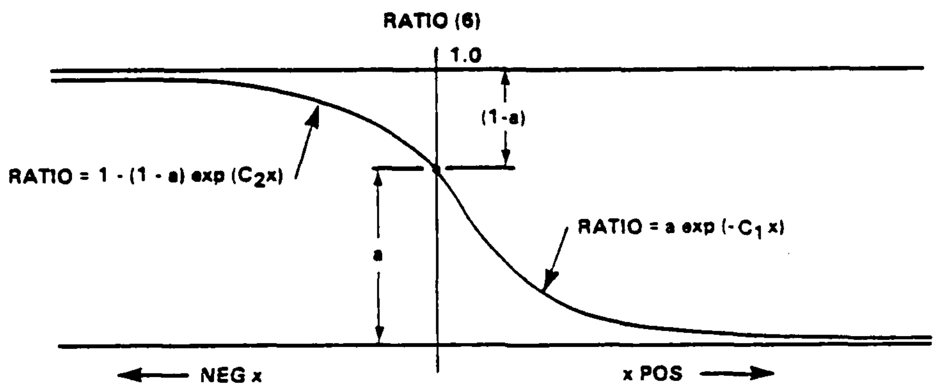

Figure 3. Ratios of Mass Flow Rates

The following summary shows where in the piping network the convergence scheme of subroutine RATIO is applied, as well as the the order of use:

1. At junction A to adjust $\dot{m}_2$
2. At junction B to adjust $\dot{m}_3$
3. At junction F to adjust $\dot{m}_{11}$
4. At junction G to adjust $\dot{m}_{14}$
5. At junction E to adjust $\dot{m}_9$
6. At junction C to adjust $\dot{m}_6$
7. At junction B for overall convergence, to adjust $\dot{m}_1$

Uses 1 and 2, above, are for the forward pass; uses 3 through 6 are for the backward pass.

THROTTLING DEVICE; FORWARD PASS

Throttling devices control, monitor, or limit flow rate in a pipe. Examples are valves, orifices, and nozzles. The effectiveness and/or discharge coefficient of such devices may be a constant or may be a function of time, Reynolds number, or some other parameter. Throttling devices are represented schematically as shown in figure 4.

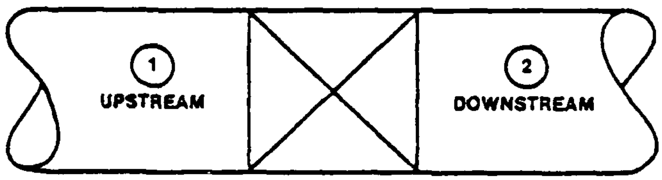

Figure 4. Throttling Device in Pipe Section

The equations used in the program to define the mass flow rate through a throttling device are taken from reference 7. These equations, which were derived for orifices with pipe taps, are as follows:

$$Y = 1 - [0.333 + 1.145\ (\beta^2 + 0.7\beta^5 + 12\beta^{13})]\ \frac{P_1 - P_2}{\gamma P_1} \qquad (1)$$

$$\dot{m} = C_D Y A[2g\rho_1(P_1 - P_2)]^{1/2} \qquad \text{(unchoked condition)} \qquad (2)$$

$$\dot{m}_{crit} = C_D A P_1 \left[\frac{2g}{RT_1}\right]^{1/2} \left[\frac{\gamma}{\gamma + 1}\left(\frac{2}{\gamma + 1}\right)^{2/(\gamma-1)}\right]^{1/2} \qquad \text{(choked condition)} \qquad (3)$$

$$P_{2\ crit} = P_{1\ crit} \left(\frac{2}{\gamma + 1}\right)^{\gamma/(\gamma-1)} \qquad (4)$$

$$P_{o2} = P_{o1} + P_2 - P_1 \qquad (5)$$

where:

A = throttling device reference area (ft^2)

C_D = discharge coefficient

g = acceleration of gravity (ft/s^2)

$\dot{m}$ = mass flow rate (lbm/s)

P_1 = upstream pressure (lb/ft^2)

P_2 = downstream pressure (lb/ft^2)

R = gas constant [(ft-lbf)/(lbm-^oR)] (53.3 for air)

T = temperature (^oR)

β = diameter ratio (throttling device/upstream pipe)

ρ = weight density (lb/ft^3)

γ = specific heat ratio

and the subscript "o" specifies stagnation properties and "crit" specifies properties at critical (throttled or choked) flow.

The conditions upstream of the throttling device are known prior to the point in the computer program at which the throttling device calculation takes place. These known conditions include values for $\dot{m}$, M_1, P_{o1}, and T_{o1}. The calculation proceeds as follows:

1. The critical mass flow rate ($\dot{m}_{crit}$) is calculated via equation (3).

2. If $\dot{m}$ is greater than $\dot{m}_{crit}$, then the estimate of flow rate from tank 1 is too high and is reduced by $\dot{m}_{crit}/\dot{m}$. Calculations begin again from tank 1.

3. If $\dot{m} = \dot{m}_{crit}$, then the flow is choked and will pass $\dot{m}$. For this case downstream properties are calculated via equations (4) and (5).

4. If $\dot{m}$ is less than $\dot{m}_{crit}$ the flow is not choked and will pass $\dot{m}$. Downstream properties are calculated next via equations (1), (2), and (3).

THROTTLING DEVICE; BACKWARD PASS

When a throttling device is encountered in the backward pass calculations, downstream conditions (point 2 in figure 4) will be known (i.e., $\dot{m}$, M_2, P_{o2}, and T_{o2}). The main difference between the forward and backward pass throttling device calculations is that the mass flow rate is not iterated in the backward pass when $\dot{m}$ is greater than $\dot{m}_c$. Instead, the upstream pressure is adjusted to accommodate the required mass flow rate. The specific procedure is as follows:

1. Downstream static pressure, P_2, is calculated.

2. Critical upstream static pressure, $P_{1\ crit}$, is calculated via equation (4).

3. Unchoked upstream static pressure, $P_{1\ unchoked}$, is calculated via equations (1) and (2). Note that this is the upstream pressure required to produce a mass flow rate across the device equal to $\dot{m}$.

4. If $P_{1\ unchoked}$ is less than or equal to $P_{1\ crit}$, then $P_{1\ unchoked}$ is the upstream static pressure, P_1, and the upstream stagnation pressure is calculated via equation (5).

5. If $P_{1\ unchoked}$ is greater than $P_{1\ crit}$, then the flow across the device in choked and upstream stagnation pressure, P_{o1}, is calculated via equation (4). In this case, when total convergence for the entire network is satisfied all the properties downstream of the throttling device will have to be recalculated in a forward pass fashion. The reason for this is that the mass flow rate is so high in this line that there is a loss of stagnation pressure from the end of the line into the tank.

This concludes the calculations across a throttling device. Although most of the calculations are straightforward, calculating the unchoked upstream static pressure, $P_{1\ unchoked}$, of step 3 can be difficult. Here, this was overcome by means of a Newton-Raphson technique (reference 8). This technique was implemented by obtaining a single algebraic equation at point 1 for ρ_1 as a function of $\dot{m}$, effective area, discharge coefficient, specific heat ratio, and the static pressure at point 2. This equation, which was solved by the Newton-Raphson technique for ρ_1, is as follows:

$$\frac{\dot{m}}{C^* \left[2g(\rho_1{}^2 RT_o - G - \rho_1 P_2)\right]^{1/2}} = 1 - \frac{D}{\gamma}\left(1 - \frac{P_2}{(\rho_1 RT_o - \frac{G}{\rho_1})}\right)$$

where

C^* is the product of discharge coefficient (C_D) and the effective area of the throttling device,

$$G = \frac{\gamma - 1}{2\gamma g}\left(\frac{\dot{m}}{A_1}\right)^2 ,$$

and

$$D = \frac{\dot{m}^2}{A_1{}^2 g \gamma RT_o} .$$

Next, an equation was derived to calculate the static pressure at point 1 in terms of ρ_1:

$$P_1 = \rho_1 RT_o - \frac{\gamma - 1}{2g\gamma}\left(\frac{\dot{m}}{A_1}^2\right)\frac{1}{\rho_1} ,$$

which is the value for unchoked static pressure at point 1.

PROGRAM STRUCTURE

MAIN PROGRAM

The main program (program MAIN) initializes all constants and reads all input data from an input file. Next, the initial estimate for the controlled flow rate from tank 1 is specified via the terminal. Once all the data are fed into the computer, program MAIN calls various subroutines to calculate the pressures and flows at the pipe junctions throughout the system.

Program MAIN calls subroutine CTANK to calculate pressures in all pipes leading away from the input tanks. Subroutine REVERSE is called upon to calculate the pressures and flow rates from the receiving tanks back to junction D. Once the flow is known at junction D, subroutine REVERSE calculates all necessary pressures and flow rates in the parallel branch. REVERSE then evaluates the pressure and flow rate in the last pipe (section 5) of the backward pass to the common point, junction B.

Program MAIN then checks the difference in stagnation pressure at the common point. If the difference is large, MAIN will change the control flow rate via subroutine RATIO, and will repeat the entire calculation procedure until agreement is reached and state conditions at all junctions of the flow network are satisfied. MAIN will print the results, increment the time step, and repeat the procedure.

Appendix A presents flowcharts of the main program and major subroutines. A brief description of the subroutines follows.

MAIN SUBROUTINES

Subroutine PRES calculates the end pressure for a pipe length in the forward pass under the assumption that specific heat ratio, gas constant, mass flow rate, stagnation temperature, stagnation pressure, pipe dimension, and pipe length are known.

Subroutine TANKPR calculates tank stagnation pressure at the end of each *time step using a Runge-Kutta integration.*

Subroutine BKVALVE performs throttling device and pipe flow calculations for the backward pass.

Subroutine FVALVE performs throttling device calculations for the forward pass.

Subroutine CTANK calculates end pressures and flow rates of pipes leaving the tanks in the forward pass network and in pipe section 4.

Subroutine RATIO, the convergence subroutine, adjusts the flow rate, using an exponential function, until the correct value for the flow rate is found.

Subroutine REVERSE controls the backward direction calculations, which calculate end pressure and flow rate for all junctions between the common point and the receiving tanks. It also calculates all pipe length pressures and flow rates in the backward pass.

REAL FUNCTION SUBROUTINES

Real function FRIC determines the Darcy friction factor at a point in the pipe where the Mach number, stagnation temperature, stagnation pressure, specific heat ratio, gas constant, mass flow rate, and pipe diameter are known.

Real function DYNVIS uses Sutherland's equation (reference 9) to calculate the dynamic viscosity.

Real function MALPHA calculates the Mach number at the end of the pipe length (outlet condition), using $\bar{f}L^*/D$ ratios:

$$\bar{f}L^*/D = (\bar{f}L^*/D)_{inlet} - (\bar{f}L^*/D)_{outlet}$$

where L^* is the length of duct required to develop a flow from the Mach number at the position under consideration to the sonic point, $\bar{f}$ is the average friction factor, and D is the pipe diameter.

Real function BETA solves the equation that relates Mach number to friction given a known Mach number, M, and specific heat ratio, γ:

$$\bar{f}L^*/D = \frac{1 - M}{\gamma M^2} + \frac{\gamma + 1}{2\gamma} \ln \frac{(\gamma + 1)M^2}{2 + (\gamma - 1)M^2} \quad .$$

Real function FF is a digital equivalent of the Moody chart for friction factor as a function of pipe roughness and Reynolds number. (Units are in feet with roughness = 0.00015 for commercial steel pipe.)

Real function MARAT calculates the Mach number at the pipe inlet.

Real function TEMP calculates the temperature at any point given the Mach number and specific heat ratio.

Real function CVEL calculates the speed of sound for a specified temperature.

Real function VEL calculates the velocity of the fluid at any point in the pipe given the Mach number.

Real function RHO calculates the density of the fluid at any point in the pipe given the Mach number and velocity.

Real function REND calculates the Reynolds number at any point given the Mach number, temperature, density, and velocity.

DEFINING THE NETWORK

ORGANIZATION OF INPUT DATA

Input data for the compressible pipe flow computer program is set by the user via a computer file. Figure 1 is the model for the input data, and networks up to the complexity shown in figure 1 can be simulated. Tank 1 must always be present, but any of the other tanks can be deleted as long as at least one receiving tank is available. Pipe sections can also be deleted as long as continuity in the flow path is maintained. Each pipe section can be defined by up to 10 individual pipe lengths, each with its corresponding diameter. Throttling devices are substituted for pipe lengths, but they cannot be located as the first or last lengths of a pipe section. This is of no serious consequence, since if a throttling device located at the end of a pipe section in a real network must be simulated, a relatively short pipe length of large diameter (which would have a negligible effect on the calculations) can be input in the simulation after the throttling device. The organization of the input file (see appendix B for a sample input data file) is as follows:

Line 1 - Identification line for the problem as defined in columns 1 to 110 of the data file.

Line 2 - Stagnation temperature (^{o}R) in the network. The FORTRAN format is F10.4.

Line 3 - Initial stagnation pressure (lb/ft^2) in each tank. The format for this line is 7F10.4 and is in the following tank order: 1, 2, 3, 11, 12, 13, 14. If a tank is not present, stagnation pressure of 0.0 is input.

Line 4 - Initial volume (ft^3) of each tank. The format for this line is 7F10.4. Tank order is the same as for line 3. If a tank is not present, volume 0.0 is input.

Line 5 - Flags specifying which tanks are in the system. Format is 7I4. Tank order is the same as for line 3. An integer value of 1 is used if a tank is in the system; 2 if a tank is not in the system.

Line 6 - Flags to specify the conditions in each tank. The format for this line is 7I4 with the tank order the same as for line 3. An integer value of 0 is used if a tank is not present; 1 for constant pressure; 2 for constant volume; 3 for variable volume defined by user-supplied differential equation.

Lines 7-8 - The number of different pipe lengths in each pipe section. Maximum is 10. Format is 7I4. Information is given in the following order:

Line 7: Pipe sections no. 1, 2, 3, 4, 5, 6, 7

Line 8: Pipe sections no. 8, 9, 10, 11, 12, 13, 14

If a pipe section is not present in the network an integer value of 0 is input. Each throttling device counts as a single pipe length.

Lines 9+ - Pipe length and diameter data (ft) for each pipe listed in lines 7 and 8. For each pipe section present in the network as shown in the order given in lines 7 and 8, two lines of information are required. The first specifies the length of each pipe in that section in the order of direction of flow; the format is 10F10.4. The second line contains the diameter data in the same order and format as the length data. Even though the format of each line is 10F10.4, only data for the number of lengths in that section are required. If a section is not present no lines of data are input for it. If a throttling device is to be simulated, a value of -99.0 is input for length and diameter. (Area and discharge coefficient data for the throttling device are inserted into the throttling device subroutines as discussed in the next section.)

Last line - Contains the values of specific heat ratio and gas constant (ft-lbf)/(lbm-^{o}R) in that order and in format 2F10.4.

THROTTLING DEVICE AND TANK CONDITIONS

Throttling device and tank condition data are still required to completely define the network. Since the respective subroutines are based on equations that are peculiar to a particular type of throttling device or tank condition, the user must edit the program to change equations and constants for discharge coefficient, area, mass flow rate, expansion factor, etc. The subroutine source listings contain comment statements to help the user.

Throttling device calculations are performed by subroutine FVALVE for pipe sections 1 through 4 and subroutine BKVALVE for pipe sections 5 through 14. In these subroutines there is a separate calculation for each pipe section so that different throttling device characteristics can be defined. The mass flow rate and expansion factor equations that are presently used in the subroutines are shown in the "Theory" section of this report. Should these not apply to a particular throttling device, then other equations must be substituted. In any case, discharge coefficient and related area must be inserted in the form of a constant or a function of time (time is transmitted to the subroutine through its argument).

Subroutine CTANK calculates tank conditions at the end of each time step using the Runge-Kutta integration scheme. When a variable volume tank condition is specified (via an integer value of 3 on line 6), the main program must calculate the rate of change of volume with respect to time via a user-supplied differential equation prior to calling the CTANK subroutine. As explained earlier, the equation to define the slope for the variable volume must be inserted into the main program. Similar to the throttling device subroutines, these calculations use separate calculation sections in the main program for each tank. The CTANK subroutine assumes an isothermal thermodynamic process between time steps, but can be changed by the user to include other processes as required.

This concludes all requirements for defining the network.

PROGRAM EXECUTION

The compressible flow computer program is presently configured to run on a Digital Equipment Corporation VAX 11/780 computer with the user providing setup data via interactive terminal. Prior to any calculations, the program asks the user for the input and output data file names, the time increment interval in number of time steps at which results are to be written to the output file, the integration time step size (s), the maximum run time (s), and the initial estimate of mass flow rate (lbm/s) from tank 1. This is all the information required to execute the program. Note that if the user sets integration time step size equal to the total run time, then the program provides a steady-state network analysis.

Program termination occurs when one of three criteria are met: when the maximum specified run time has been reached, when the pressure in the supply tank(s) is less than or equal to that in the receiving tank(s), or when flow from tank 1 has stopped. As mentioned in the "Theory" section, tank 1 is the main supply tank and controls the calculations; hence it must always produce a flow in the downstream direction.

OUTPUT

Appendix C contains the output file which resulted from executing the program using the sample input file of appendix B. Note that all input data contained in the input data file are initially written to the output file, permitting verification of input data. Results of program calculations at each time step for which results were to be written are listed next. At each output time step, the following data are written to the output file:

1. Time averaged mass flow rate (lbm/s) through each section

2. Time averaged stagnation pressure at the end of each pipe section
3. Time averaged Mach numbers at the end of each pipe section
4. Tank pressures at the end of the time step
5. Tank volumes at the end of the time step.

SUMMARY AND CONCLUSIONS

A method of calculating the transient flow of compressible fluids through complex piping networks has been developed, and a computer program implementing this method has been written. This report has documented the theory and logic upon which the solution method and computer program are based. It also serves as an introduction to the program, which was designed to be used by persons having minimum knowledge of compressible flow theory.

The program is shown to be sufficiently general to handle a wide variety of complex piping systems. Supply and receiving tanks can each be defined as having either constant volume, constant pressure, or variable volume; flow can be either steady or unsteady; flow-limiting conditions resulting from wall friction, changes in pipe diameter, and throttling devices can be simulated; and the number, length, diameter, and configuration of pipe sections can be easily varied. Numerical techniques such as Runge-Kutta integration and Newton-Raphson iteration have been incorporated in the program wherever possible. The program, besides being versatile and adaptable to a wide variety of piping networks, provides rapid solution convergence.

REFERENCES

1. T. G. Keith, Digital Computer Analysis of Submarine Emergency Deballasting System, Piping Section, DTNSRDC Report 2569, David W. Taylor Naval Ship Research and Development Center, Bethesda, MD, May 1968.

2. M. E. Wilton and J. P. Murtaugh, Compressible Flow Network Analysis, COSMIC Report No. LEW-11859, Computer Software Management and Information Center, Athens, GA, 1971.

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4. J. F. T. MacLaren, et al., Solving the Equations for Unsteady Gas Flow by Two Methods, Simulation Councils, Inc., 1976.

5. P. T. Daniel, "The Analysis of Compressible and Incompressible Fluid Networks," Transactions of the Institution of Chemical Engineers, Vol 44, 1966.

6. A. H. Shapiro, The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol 1, Ronald Press Company, New York, 1953.

7. J. P. Holman, Experimental Methods for Engineers, McGraw-Hill Book Company, New York, 1971.

8. B. Carnahan, H. A. Luther, J. O. Wilkes, Applied Numerical Methods, John Wiley and Sons, New York, 1969.

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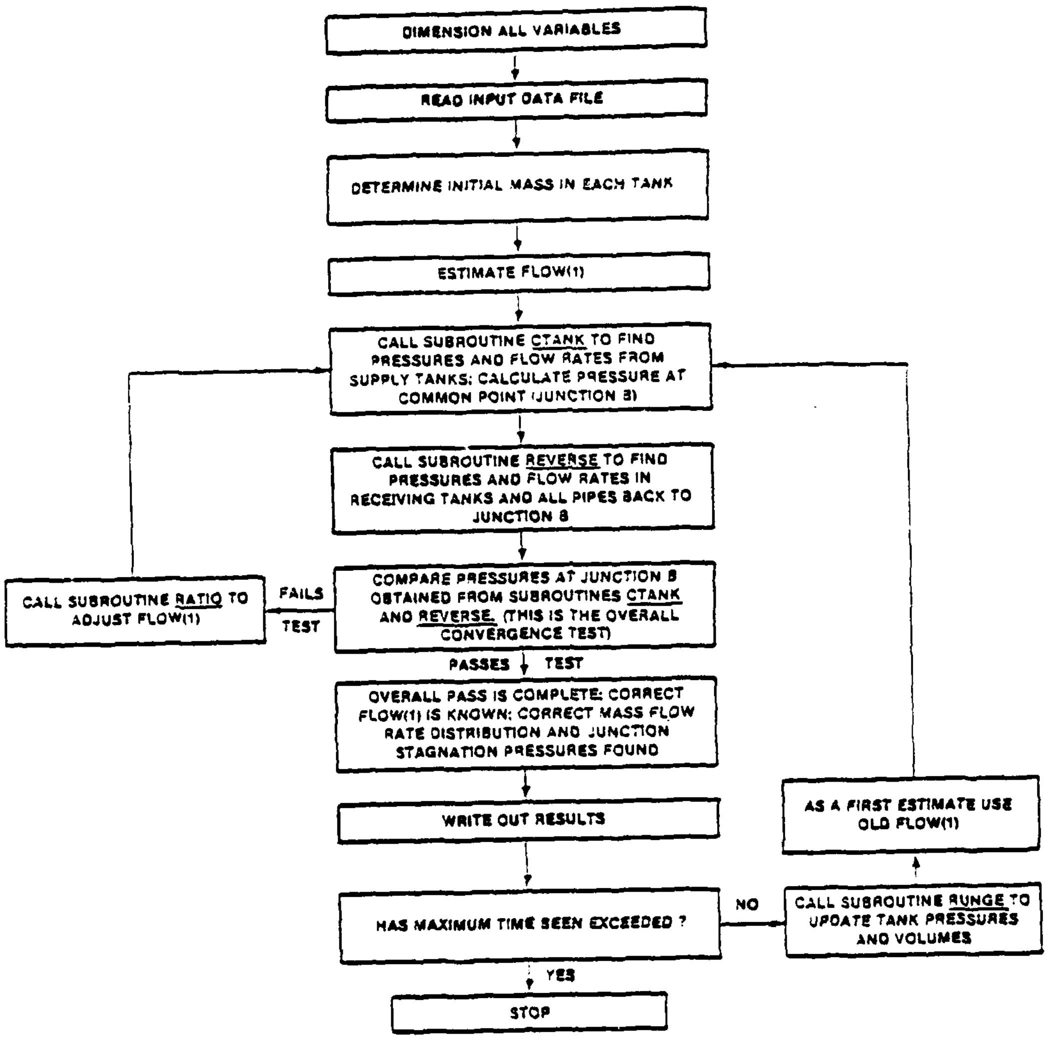
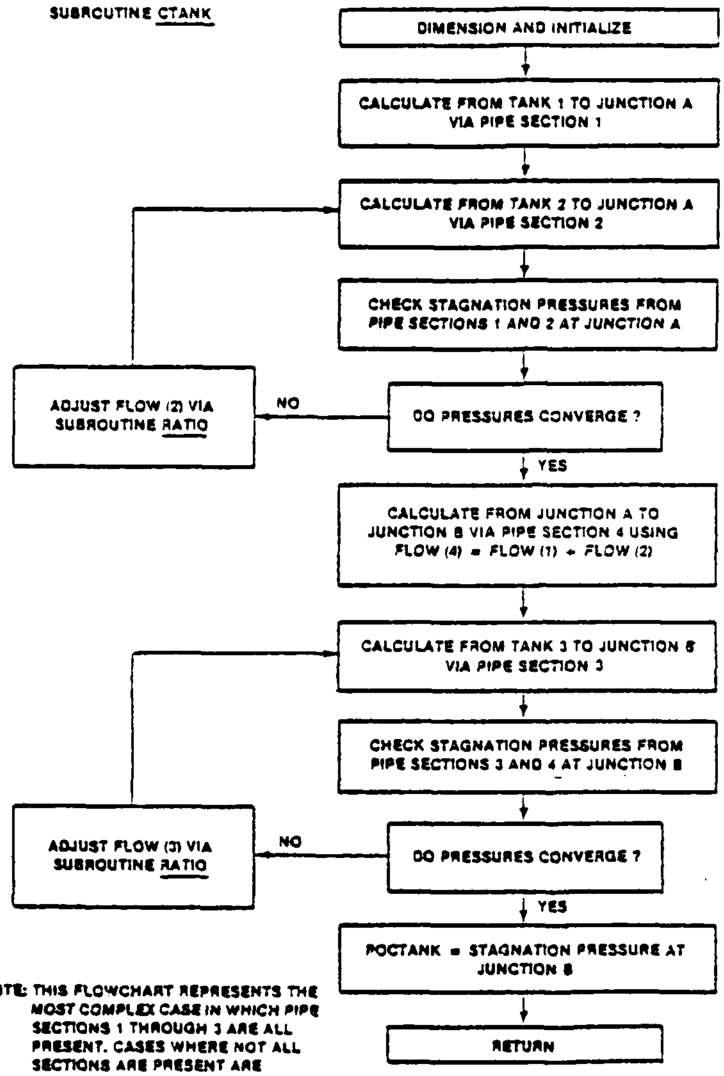
APPENDIX A

FLOWCHARTS

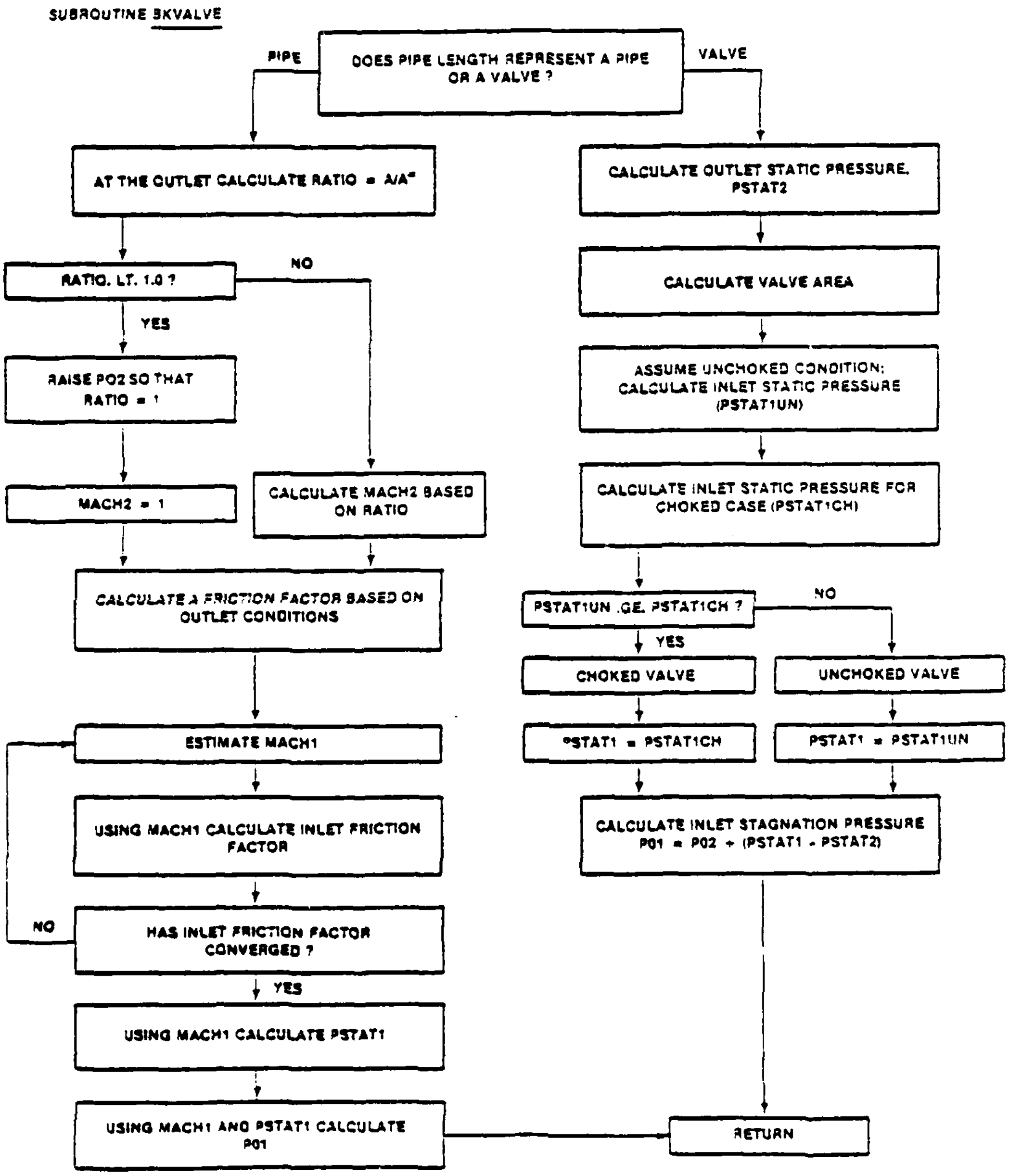
MAIN PROGRAM

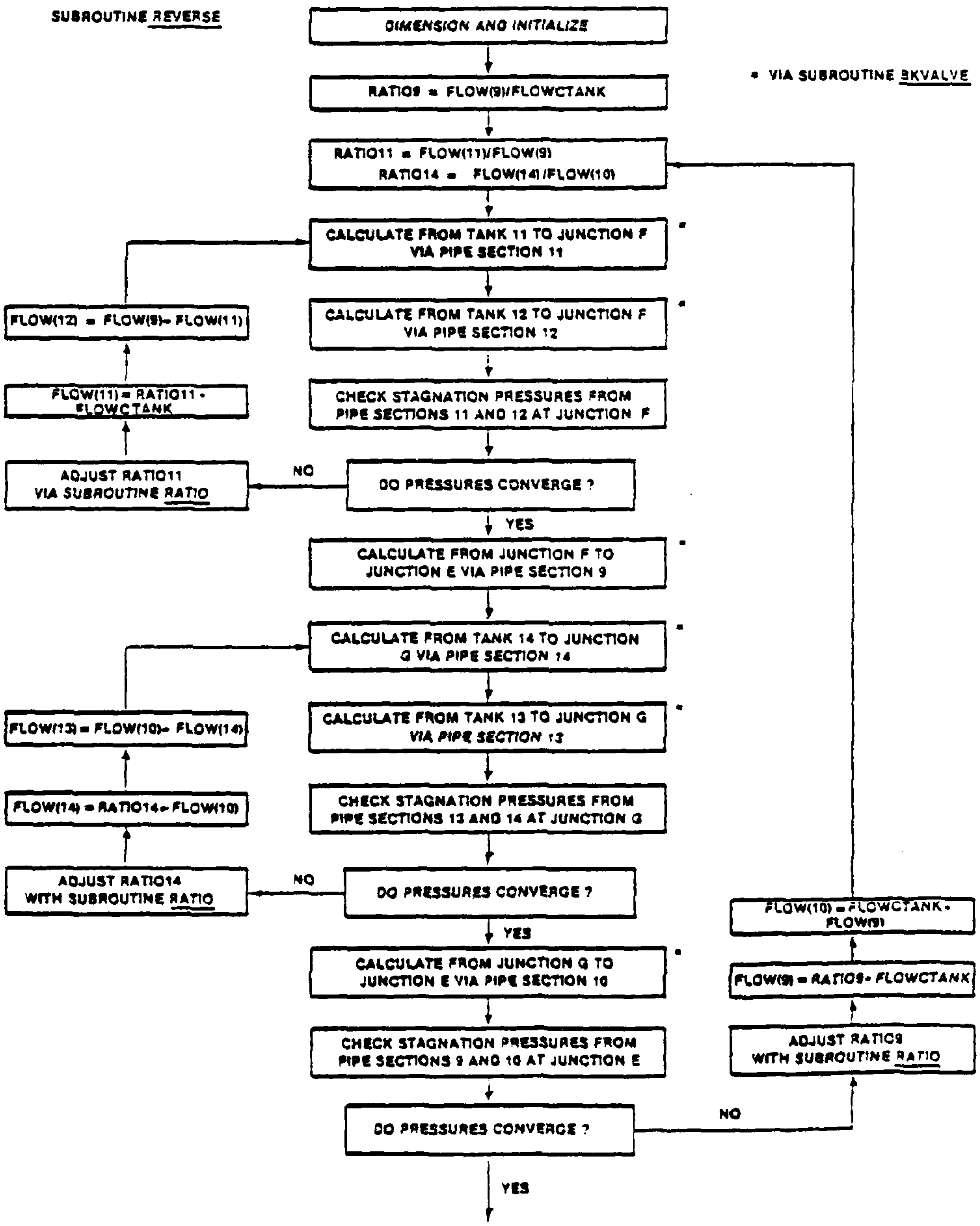


SUBROUTINE CTANK

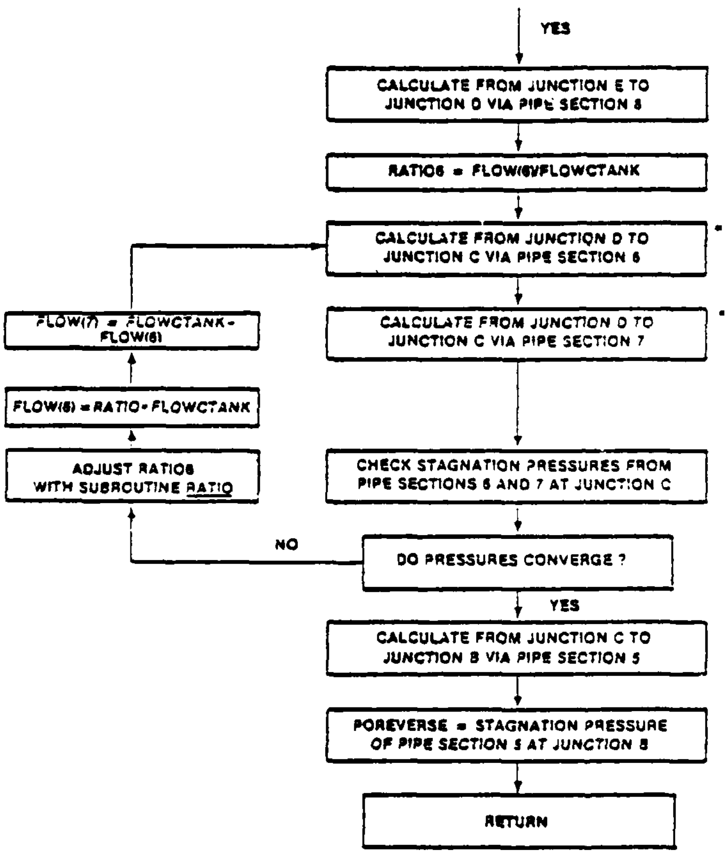


NOTE: THIS FLOWCHART REPRESENTS THE MOST COMPLEX CASE IN WHICH PIPE SECTIONS 1 THROUGH 3 ARE ALL PRESENT. CASES WHERE NOT ALL SECTIONS ARE PRESENT ARE AUTOMATICALLY HANDLED BY THE PROGRAM, WHICH COMPENSATES FOR THE MISSING SECTIONS AND VERIFIES FLOW CONTINUITY. CHOKING LOGIC, WHICH IS DETAILED IN THE BODY OF THIS REPORT AND IN THE COMPUTER PROGRAM ITSELF, HAS BEEN SUPPRESSED IN THIS FLOWCHART.


SUBROUTINE BKVALVE
DOES PIPE LENGTH REPRESENT A PIPE OR A VALVE ?
PIPE
VALVE
AT THE OUTLET CALCULATE RATIO = A/A*
RATIO. LT. 1.0 ?
NO
YES
RAISE PO2 SO THAT RATIO = 1
MACH2 = 1
CALCULATE MACH2 BASED ON RATIO
CALCULATE A FRICTION FACTOR BASED ON OUTLET CONDITIONS
ESTIMATE MACH1
USING MACH1 CALCULATE INLET FRICTION FACTOR
HAS INLET FRICTION FACTOR CONVERGED ?
NO
YES
USING MACH1 CALCULATE PSTAT1
USING MACH1 AND PSTAT1 CALCULATE P01
CALCULATE OUTLET STATIC PRESSURE, PSTAT2
CALCULATE VALVE AREA
ASSUME UNCHOKED CONDITION: CALCULATE INLET STATIC PRESSURE (PSTAT1UN)
CALCULATE INLET STATIC PRESSURE FOR CHOKED CASE (PSTAT1CH)
PSTAT1UN .GE. PSTAT1CH ?
NO
YES
CHOKED VALVE
UNCHOKED VALVE
PSTAT1 = PSTAT1CH
PSTAT1 = PSTAT1UN
CALCULATE INLET STAGNATION PRESSURE P01 = P02 + (PSTAT1 - PSTAT2)
RETURN

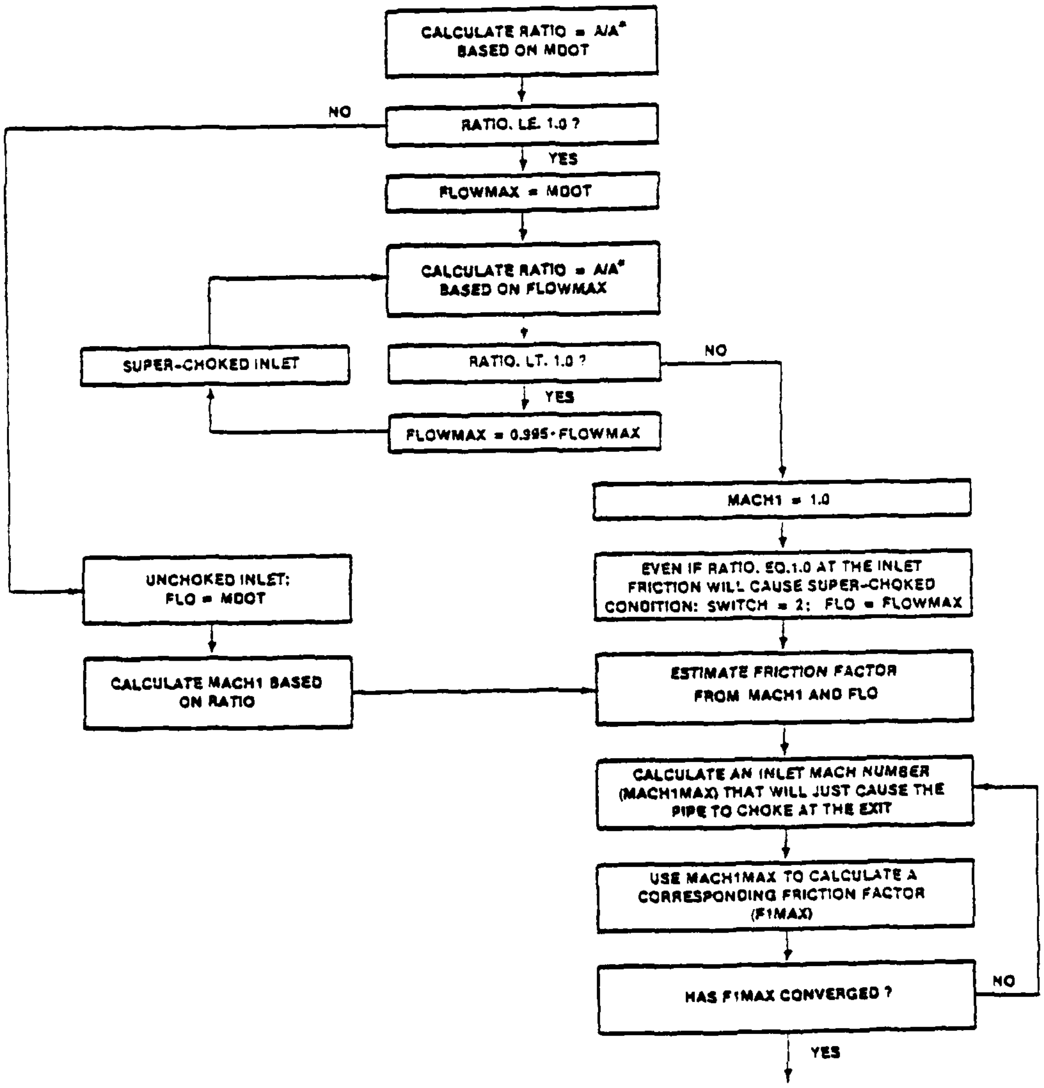

SUBROUTINE REVERSE
* VIA SUBROUTINE BKVALVE
DIMENSION AND INITIALIZE
RATIO9 = FLOW(9)/FLOWCTANK
RATIO11 = FLOW(11)/FLOW(9)
RATIO14 = FLOW(14)/FLOW(10)
CALCULATE FROM TANK 11 TO JUNCTION F VIA PIPE SECTION 11
CALCULATE FROM TANK 12 TO JUNCTION F VIA PIPE SECTION 12
CHECK STAGNATION PRESSURES FROM PIPE SECTIONS 11 AND 12 AT JUNCTION F
DO PRESSURES CONVERGE ?
NO
ADJUST RATIO11 VIA SUBROUTINE RATIO
FLOW(11) = RATIO11 · FLOWCTANK
FLOW(12) = FLOW(9)– FLOW(11)
YES
CALCULATE FROM JUNCTION F TO JUNCTION E VIA PIPE SECTION 9
CALCULATE FROM TANK 14 TO JUNCTION G VIA PIPE SECTION 14
CALCULATE FROM TANK 13 TO JUNCTION G VIA PIPE SECTION 13
CHECK STAGNATION PRESSURES FROM PIPE SECTIONS 13 AND 14 AT JUNCTION G
DO PRESSURES CONVERGE ?
NO
ADJUST RATIO14 WITH SUBROUTINE RATIO
FLOW(14) = RATIO14 · FLOW(10)
FLOW(13) = FLOW(10)– FLOW(14)
YES
CALCULATE FROM JUNCTION G TO JUNCTION E VIA PIPE SECTION 10
CHECK STAGNATION PRESSURES FROM PIPE SECTIONS 9 AND 10 AT JUNCTION E
DO PRESSURES CONVERGE ?
NO
ADJUST RATIO9 WITH SUBROUTINE RATIO
FLOW(9) = RATIO9 · FLOWCTANK
FLOW(10) = FLOWCTANK · FLOW(9)
YES

SUBROUTINE REVERSE (CONT'D)

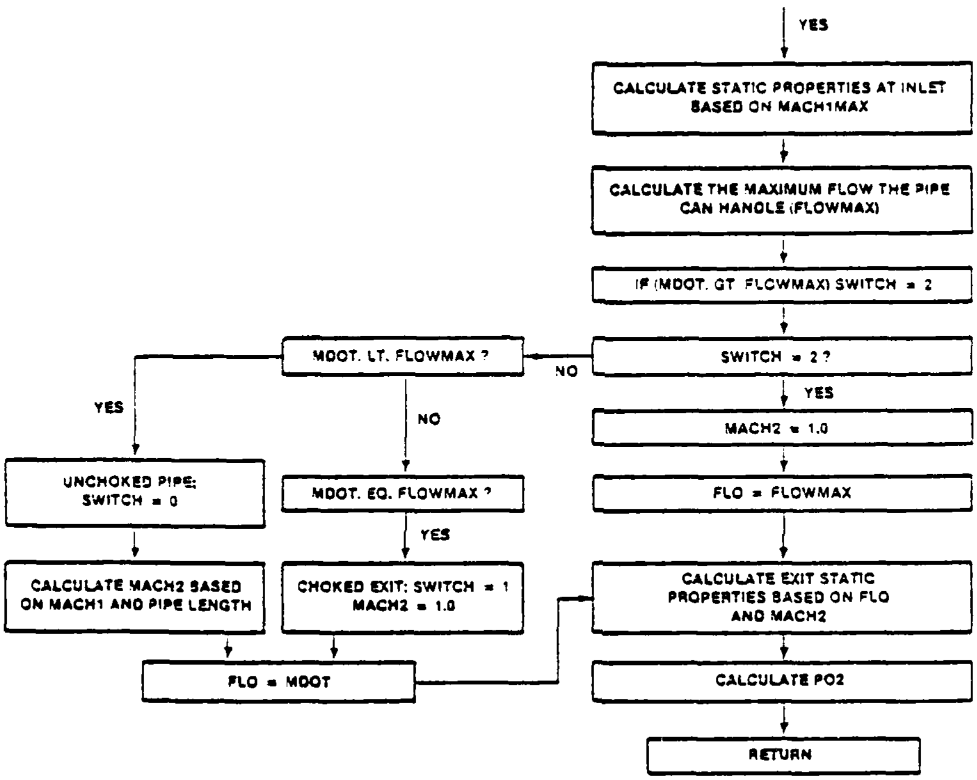


NOTE: THIS FLOWCHART REPRESENTS THE MOST COMPLEX CASE IN WHICH PIPE SECTIONS 5 THROUGH 14 ARE ALL PRESENT. CASES WHERE NOT ALL PIPE SECTIONS ARE PRESENT ARE AUTOMATICALLY HANDLED BY THE PROGRAM, WHICH COMPENSATES FOR THE MISSING SECTIONS AND VERIFIES FLOW CONTINUITY.

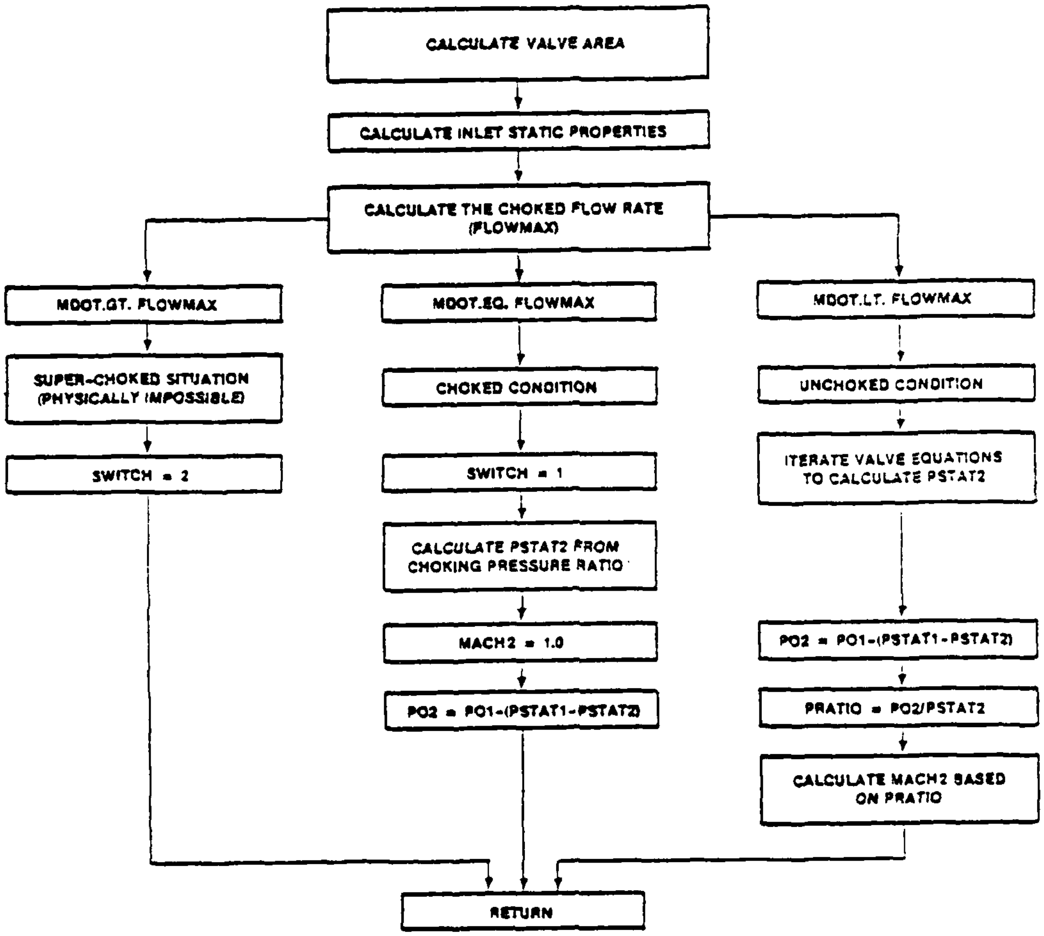
SUBROUTINE PRES



SUBROUTINE PRES (CONT'D)



SUBROUTINE FVALVE



APPENDIX B

SAMPLE INPUT DATA FILE

```
SAMPLE NETWORK
540.0
2033.0,2083.0,2033.0,100.0,140.0,100.0,140.
320.,320.,320.,200.,200.,200.,200.
1,1,1,1,1,1,1
2,2,2,2,2,2,2
3,3,3,2,2,2,2
2,2,2,2,2,2,2
12.,13.,14.
.111,.080,.070
13.,14.,12.
.035,.081,.077
14.,16.,15.
.075,.081,.077
13.,-99
.039,.111
15.,16.
.125,.105
14.,16.
.099,.085
13.,15.
.155,.166
15.,12.
.175,.185
10.,13.
.085,.088
12.,9.
.079,.083
13.,-99.
.071,.083
11.,11.
.099,.083
12.,13.
.111,.125
12.,9.
.102,.101
1.4,53.3
```

APPENDIX C

SAMPLE OUTPUT DATA FILE

```
SAMPLE NETWORK

INPUT DATA LISTING
INPUT DATA FILENAME = INPUT

STAGNATION TEMPERATURE =   540.0000 DEGREES RANKINE
SPECIFIC HEAT RATIO =    1.4000
GAS CONSTANT =   53.3000 FT/DEGREES RANKINE

TANK DATA

TANK #   1          STAGNATION PRESSURE =    2750.00 LB/IN**2          VOLUME =      32.00 FT**3

TANK #   2          STAGNATION PRESSURE =    2750.00 LB/IN**2          VOLUME =      32.00 FT**3

TANK #   3          STAGNATION PRESSURE =    2750.00 LB/IN**2          VOLUME =      32.00 FT**3

TANK #  11          STAGNATION PRESSURE =     225.00 LB/IN**2          VOLUME =      20.00 FT**3

TANK #  12          STAGNATION PRESSURE =     140.00 LB/IN**2          VOLUME =      20.00 FT**3

TANK #  13          STAGNATION PRESSURE =     225.00 LB/IN**2          VOLUME =      20.00 FT**3

TANK #  14          STAGNATION PRESSURE =     140.00 LB/IN**2          VOLUME =      20.00 FT**3

NETWORK PIPING GEOMETRY

PIPE SECTION #    1    PIPE #    1          LENGTH =  12.0000 FT    DIAMETER =    0.1110 FT
PIPE SECTION #    1    PIPE #    2          LENGTH =  13.0000 FT    DIAMETER =    0.0900 FT
PIPE SECTION #    1    PIPE #    3          LENGTH =  14.0000 FT    DIAMETER =    0.0700 FT
PIPE SECTION #    2    PIPE #    1          LENGTH =  13.0000 FT    DIAMETER =    0.0350 FT
PIPE SECTION #    2    PIPE #    2          LENGTH =  14.0000 FT    DIAMETER =    0.0910 FT
PIPE SECTION #    2    PIPE #    3          LENGTH =  12.0000 FT    DIAMETER =    0.0770 FT
PIPE SECTION #    3    PIPE #    1          LENGTH =  14.0000 FT    DIAMETER =    0.0750 FT
PIPE SECTION #    3    PIPE #    2          LENGTH =  16.0000 FT    DIAMETER =    0.0910 FT
PIPE SECTION #    3    PIPE #    3          LENGTH =  15.0000 FT    DIAMETER =    0.0770 FT
PIPE SECTION #    4    PIPE #    1          LENGTH =  13.0000 FT    DIAMETER =    0.0990 FT
PIPE SECTION #    4    PIPE #    2          LENGTH =  18.0000 FT    DIAMETER =    0.1110 FT
PIPE SECTION #    5    PIPE #    1          LENGTH =  15.0000 FT    DIAMETER =    0.1250 FT
PIPE SECTION #    5    PIPE #    2  IS A CONTROL DEVICE
PIPE SECTION #    5    PIPE #    3          LENGTH =  15.0000 FT    DIAMETER =    0.0980 FT
PIPE SECTION #    6    PIPE #    1          LENGTH =  14.0000 FT    DIAMETER =    0.0990 FT
PIPE SECTION #    6    PIPE #    2          LENGTH =  16.0000 FT    DIAMETER =    0.0850 FT
PIPE SECTION #    7    PIPE #    1          LENGTH =  13.0000 FT    DIAMETER =    0.1550 FT
PIPE SECTION #    7    PIPE #    2          LENGTH =  15.0000 FT    DIAMETER =    0.1660 FT
PIPE SECTION #    8    PIPE #    1          LENGTH =  15.0000 FT    DIAMETER =    0.1750 FT
PIPE SECTION #    8    PIPE #    2          LENGTH =  12.0000 FT    DIAMETER =    0.1350 FT
PIPE SECTION #    9    PIPE #    1          LENGTH =  10.0000 FT    DIAMETER =    0.0350 FT
PIPE SECTION #    9    PIPE #    2          LENGTH =  13.0000 FT    DIAMETER =    0.0890 FT
PIPE SECTION #   10    PIPE #    1          LENGTH =  12.0000 FT    DIAMETER =    0.0790 FT
PIPE SECTION #   10    PIPE #    2          LENGTH =   9.0000 FT    DIAMETER =    0.0320 FT
PIPE SECTION #   11    PIPE #    1          LENGTH =  13.0000 FT    DIAMETER =    0.0710 FT
PIPE SECTION #   11    PIPE #    2          LENGTH =  18.0000 FT    DIAMETER =    0.0330 FT
PIPE SECTION #   12    PIPE #    1          LENGTH =  11.0000 FT    DIAMETER =    0.0650 FT
PIPE SECTION #   12    PIPE #    2          LENGTH =  11.0000 FT    DIAMETER =    0.0760 FT
PIPE SECTION #   13    PIPE #    1          LENGTH =  12.0000 FT    DIAMETER =    0.0450 FT
PIPE SECTION #   13    PIPE #    2          LENGTH =  13.0000 FT    DIAMETER =    0.1250 FT
PIPE SECTION #   14    PIPE #    1          LENGTH =  12.0000 FT    DIAMETER =    0.1020 FT
PIPE SECTION #   14    PIPE #    2          LENGTH =   9.0000 FT    DIAMETER =    0.1010 FT
```

APPENDIX C

SAMPLE OUTPUT DATA FILE

```
SAMPLE NETWORK

INPUT DATA LISTING
INPUT DATA FILENAME = INPUT

STAGNATION TEMPERATURE =    540.0000 DEGREES RANKINE
SPECIFIC HEAT RATIO =      1.4000
GAS CONSTANT =    53.3000 FT/DEGREES RANKINE

TANK DATA

TANK #   1          STAGNATION PRESSURE =    2750.00 LB/IN**2          VOLUME =     32.00 FT**3

TANK #   2          STAGNATION PRESSURE =    2750.00 LB/IN**2          VOLUME =     32.00 FT**3

TANK #   3          STAGNATION PRESSURE =    2750.00 LB/IN**2          VOLUME =     32.00 FT**3

TANK #  11          STAGNATION PRESSURE =     225.00 LB/IN**2          VOLUME =     20.00 FT**3

TANK #  12          STAGNATION PRESSURE =     140.00 LB/IN**2          VOLUME =     20.00 FT**3

TANK #  13          STAGNATION PRESSURE =     225.00 LB/IN**2          VOLUME =     20.00 FT**3

TANK #  14          STAGNATION PRESSURE =     140.00 LB/IN**2          VOLUME =     20.00 FT**3

NETWORK PIPING GEOMETRY

PIPE SECTION #    1     PIPE #    1          LENGTH =   12.0000 FT     DIAMETER =    0.1110 FT
PIPE SECTION #    1     PIPE #    2          LENGTH =   13.0000 FT     DIAMETER =    0.0900 FT
PIPE SECTION #    1     PIPE #    3          LENGTH =   14.0000 FT     DIAMETER =    0.0700 FT
PIPE SECTION #    2     PIPE #    1          LENGTH =   13.0000 FT     DIAMETER =    0.0350 FT
PIPE SECTION #    2     PIPE #    2          LENGTH =   14.0000 FT     DIAMETER =    0.0910 FT
PIPE SECTION #    2     PIPE #    3          LENGTH =   12.0000 FT     DIAMETER =    0.0770 FT
PIPE SECTION #    3     PIPE #    1          LENGTH =   14.0000 FT     DIAMETER =    0.0750 FT
PIPE SECTION #    3     PIPE #    2          LENGTH =   16.0000 FT     DIAMETER =    0.0310 FT
PIPE SECTION #    3     PIPE #    3          LENGTH =   15.0000 FT     DIAMETER =    0.0770 FT
PIPE SECTION #    4     PIPE #    1          LENGTH =   13.0000 FT     DIAMETER =    0.0990 FT
PIPE SECTION #    4     PIPE #    2          LENGTH =   18.0000 FT     DIAMETER =    0.1110 FT
PIPE SECTION #    5     PIPE #    1          LENGTH =   15.0000 FT     DIAMETER =    0.1250 FT
PIPE SECTION #    5     PIPE #    2  IS A CONTROL DEVICE
PIPE SECTION #    5     PIPE #    3          LENGTH =   15.0000 FT     DIAMETER =    0.0980 FT
PIPE SECTION #    6     PIPE #    1          LENGTH =   14.0000 FT     DIAMETER =    0.0990 FT
PIPE SECTION #    6     PIPE #    2          LENGTH =   16.0000 FT     DIAMETER =    0.0850 FT
PIPE SECTION #    7     PIPE #    1          LENGTH =   13.0000 FT     DIAMETER =    0.1550 FT
PIPE SECTION #    7     PIPE #    2          LENGTH =   15.0000 FT     DIAMETER =    0.1660 FT
PIPE SECTION #    8     PIPE #    1          LENGTH =   15.0000 FT     DIAMETER =    0.1750 FT
PIPE SECTION #    8     PIPE #    2          LENGTH =   12.0000 FT     DIAMETER =    0.1350 FT
PIPE SECTION #    9     PIPE #    1          LENGTH =   10.0000 FT     DIAMETER =    0.0350 FT
PIPE SECTION #    9     PIPE #    2          LENGTH =   13.0000 FT     DIAMETER =    0.0890 FT
PIPE SECTION #   10     PIPE #    1          LENGTH =   12.0000 FT     DIAMETER =    0.0790 FT
PIPE SECTION #   10     PIPE #    2          LENGTH =    9.0000 FT     DIAMETER =    0.0390 FT
PIPE SECTION #   11     PIPE #    1          LENGTH =   13.0000 FT     DIAMETER =    0.0710 FT
PIPE SECTION #   11     PIPE #    2          LENGTH =   18.0000 FT     DIAMETER =    0.0330 FT
PIPE SECTION #   12     PIPE #    1          LENGTH =   11.0000 FT     DIAMETER =    0.0650 FT
PIPE SECTION #   12     PIPE #    2          LENGTH =   11.0000 FT     DIAMETER =    0.0760 FT
PIPE SECTION #   13     PIPE #    1          LENGTH =   12.0000 FT     DIAMETER =    0.0450 FT
PIPE SECTION #   13     PIPE #    2          LENGTH =   13.0000 FT     DIAMETER =    0.1250 FT
PIPE SECTION #   14     PIPE #    1          LENGTH =   12.0000 FT     DIAMETER =    0.1020 FT
PIPE SECTION #   14     PIPE #    2          LENGTH =    9.0000 FT     DIAMETER =    0.1010 FT
```

RESULTS AT END OF TIME STEP # 0
TIME = 0.00000 SEC

RESULTS AT END OF PIPE SECTIONS 1 TO 14

PIPE # 1	MACH #	0.1358	FLOW RATE	7.4336	LBM/SEC	STAGNATION PRESSURE	2522.7 LBF/IN**2
PIPE # 2	MACH #	0.1211	FLOW RATE	9.0357	LBM/SEC	STAGNATION PRESSURE	2523.0 LBF/IN**2
PIPE # 3	MACH #	0.1631	FLOW RATE	9.6173	LBM/SEC	STAGNATION PRESSURE	2256.9 LBF/IN**2
PIPE # 4	MACH #	0.1257	FLOW RATE	15.4693	LBM/SEC	STAGNATION PRESSURE	2252.2 LBF/IN**2
PIPE # 5	MACH #	0.3894	FLOW RATE	25.0855	LBM/SEC	STAGNATION PRESSURE	1639.3 LBF/IN**2
PIPE # 6	MACH #	0.0900	FLOW RATE	4.5945	LBM/SEC	STAGNATION PRESSURE	1585.5 LBF/IN**2
PIPE # 7	MACH #	0.1055	FLOW RATE	20.4921	LBM/SEC	STAGNATION PRESSURE	1585.5 LBF/IN**2
PIPE # 8	MACH #	0.1067	FLOW RATE	25.0865	LBM/SEC	STAGNATION PRESSURE	1544.3 LBF/IN**2
PIPE # 9	MACH #	0.3633	FLOW RATE	12.3246	LBM/SEC	STAGNATION PRESSURE	1038.2 LBF/IN**2
PIPE #10	MACH #	0.5600	FLOW RATE	12.7620	LBM/SEC	STAGNATION PRESSURE	789.1 LBF/IN**2
PIPE #11	MACH #	1.0000	FLOW RATE	6.5106	LBM/SEC	STAGNATION PRESSURE	225.0 LBF/IN**2
PIPE #12	MACH #	1.0000	FLOW RATE	5.3160	LBM/SEC	STAGNATION PRESSURE	140.0 LBF/IN**2
PIPE #13	MACH #	0.1169	FLOW RATE	1.3251	LBM/SEC	STAGNATION PRESSURE	225.0 LBF/IN**2
PIPE #14	MACH #	1.0000	FLOW RATE	10.9369	LBM/SEC	STAGNATION PRESSURE	140.0 LBF/IN**2

RESULTS AT END OF TIME STEP # 1
TIME = 0.50000 SEC

TANK RESULTS

TANK # 1	STAGNATION PRESSURE =	2726.78 LB/IN**2	VOLUME = 32.0000 FT**3
TANK # 2	STAGNATION PRESSURE =	2724.90 LB/IN**2	VOLUME = 32.0000 FT**3
TANK # 3	STAGNATION PRESSURE =	2719.96 LB/IN**2	VOLUME = 32.0000 FT**3
TANK # 11	STAGNATION PRESSURE =	257.53 LB/IN**2	VOLUME = 20.0000 FT**3
TANK # 12	STAGNATION PRESSURE =	163.05 LB/IN**2	VOLUME = 20.0000 FT**3
TANK # 13	STAGNATION PRESSURE =	234.12 LB/IN**2	VOLUME = 20.0000 FT**3
TANK # 14	STAGNATION PRESSURE =	194.65 LB/IN**2	VOLUME = 20.0000 FT**3

RESULTS AT END OF PIPE SECTIONS 1 TO 14

PIPE # 1	MACH #	0.1360	FLOW RATE	7.3782	LBM/SEC	STAGNATION PRESSURE	2500.9 LBF/IN**2
PIPE # 2	MACH #	0.1213	FLOW RATE	7.9759	LBM/SEC	STAGNATION PRESSURE	2499.1 LBF/IN**2
PIPE # 3	MACH #	0.1640	FLOW RATE	9.5456	LBM/SEC	STAGNATION PRESSURE	2229.3 LBF/IN**2
PIPE # 4	MACH #	0.1260	FLOW RATE	15.3541	LBM/SEC	STAGNATION PRESSURE	2230.9 LBF/IN**2
PIPE # 5	MACH #	0.3894	FLOW RATE	24.8998	LBM/SEC	STAGNATION PRESSURE	1627.1 LBF/IN**2
PIPE # 6	MACH #	0.0900	FLOW RATE	4.5603	LBM/SEC	STAGNATION PRESSURE	1573.7 LBF/IN**2
PIPE # 7	MACH #	0.1055	FLOW RATE	20.3395	LBM/SEC	STAGNATION PRESSURE	1573.7 LBF/IN**2
PIPE # 8	MACH #	0.1067	FLOW RATE	24.8998	LBM/SEC	STAGNATION PRESSURE	1523.3 LBF/IN**2
PIPE # 9	MACH #	0.3633	FLOW RATE	12.2328	LBM/SEC	STAGNATION PRESSURE	1050.4 LBF/IN**2
PIPE #10	MACH #	0.5600	FLOW RATE	12.6670	LBM/SEC	STAGNATION PRESSURE	783.3 LBF/IN**2
PIPE #11	MACH #	1.0000	FLOW RATE	6.4621	LBM/SEC	STAGNATION PRESSURE	257.5 LBF/IN**2
PIPE #12	MACH #	1.0000	FLOW RATE	5.7707	LBM/SEC	STAGNATION PRESSURE	163.1 LBF/IN**2
PIPE #13	MACH #	0.1115	FLOW RATE	1.3115	LBM/SEC	STAGNATION PRESSURE	234.1 LBF/IN**2
PIPE #14	MACH #	1.0000	FLOW RATE	10.3555	LBM/SEC	STAGNATION PRESSURE	194.7 LBF/IN**2

RESULTS AT END OF TIME STEP # 2
TIME = 1.00000 SEC

TANK RESULTS

TANK # 1	STAGNATION PRESSURE =	2703.74	LB/IN**2	VOLUME =	32.0000	FT**3
TANK # 2	STAGNATION PRESSURE =	2700.00	LB/IN**2	VOLUME =	32.0000	FT**3
TANK # 3	STAGNATION PRESSURE =	2690.15	LB/IN**2	VOLUME =	32.0000	FT**3
TANK # 11	STAGNATION PRESSURE =	289.82	LB/IN**2	VOLUME =	20.0000	FT**3
TANK # 12	STAGNATION PRESSURE =	197.39	LB/IN**2	VOLUME =	20.0000	FT**3
TANK # 13	STAGNATION PRESSURE =	243.17	LB/IN**2	VOLUME =	20.0000	FT**3
TANK # 14	STAGNATION PRESSURE =	248.39	LB/IN**2	VOLUME =	20.0000	FT**3

RESULTS AT END OF PIPE SECTIONS 1 TO 14

PIPE # 1	MACH # 0.1368	FLOW RATE	7.3519	LBM/SEC	STAGNATION PRESSURE 2477.4	LBF/IN**2
PIPE # 2	MACH # 0.1222	FLOW RATE	7.3475	LBM/SEC	STAGNATION PRESSURE 2473.6	LBF/IN**2
PIPE # 3	MACH # 0.1631	FLOW RATE	9.4054	LBM/SEC	STAGNATION PRESSURE 2203.1	LBF/IN**2
PIPE # 4	MACH # 0.1270	FLOW RATE	15.2934	LBM/SEC	STAGNATION PRESSURE 2205.3	LBF/IN**2
PIPE # 5	MACH # 0.3834	FLOW RATE	24.7048	LBM/SEC	STAGNATION PRESSURE 1614.3	LBF/IN**2
PIPE # 6	MACH # 0.3900	FLOW RATE	4.5218	LBM/SEC	STAGNATION PRESSURE 1561.4	LBF/IN**2
PIPE # 7	MACH # 0.1055	FLOW RATE	20.1630	LBM/SEC	STAGNATION PRESSURE 1561.4	LBF/IN**2
PIPE # 8	MACH # 0.1067	FLOW RATE	24.7048	LBM/SEC	STAGNATION PRESSURE 1521.3	LBF/IN**2
PIPE # 9	MACH # 0.2633	FLOW RATE	12.1601	LBM/SEC	STAGNATION PRESSURE 1044.1	LBF/IN**2
PIPE #10	MACH # 0.5600	FLOW RATE	12.5447	LBM/SEC	STAGNATION PRESSURE 775.7	LBF/IN**2
PIPE #11	MACH # 1.0000	FLOW RATE	6.4237	LBM/SEC	STAGNATION PRESSURE 289.8	LBF/IN**2
PIPE #12	MACH # 1.0000	FLOW RATE	5.7364	LBM/SEC	STAGNATION PRESSURE 197.9	LBF/IN**2
PIPE #13	MACH # 0.1062	FLOW RATE	1.7940	LBM/SEC	STAGNATION PRESSURE 243.2	LBF/IN**2
PIPE #14	MACH # 1.0000	FLOW RATE	10.7507	LBM/SEC	STAGNATION PRESSURE 243.9	LBF/IN**2