THESIS

CONDENSATION OF REFRIGERANTS ON SMALL TUBE BUNDLES

by

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December 1988

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Condensation of Refrigerants on Small Tube Bundles

by

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ABSTRACT

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NOMENCLATURE

\( A_{ef} \)  Effective outside area of the tube (m²)

\( A_f \)  Actual area of a finned tube (m²)

\( A_i \)  Tube inside area (m²)

\( A_o \)  Tube outside area (m²)

\( A_r \)  Surface area of tube at the base of the fin (m²)

\( C_i \)  Inside correlation coefficient

\( C_o \)  Outside correlation coefficient

\( C_p \)  Specific heat of coolant (J/kg K)

\( D_{eq} \)  Equivalent diameter of finned tube (m)

\( D_i \)  Inside diameter of test tube (m)

\( D_o \)  Outside diameter of test tube (m)

\( D_r \)  Root diameter of finned tube (m)

\( g \)  Acceleration due to gravity (m/s²)

\( L \)  Length of the condenser tube (m)

\( \text{LMTD} \)  Log mean temperature difference (K)

\( N \)  Number of the tube from top of bundle

\( \text{Ph} \)  Phase Change Number

\( \text{Pr} \)  Prandtl Number

\( Q \)  Heat-transfer rate (W)

\( Q'' \)  Heat-flux (W/m²)

\( \text{Re} \)  Reynolds Number

\( \text{Rm} \)  Tube wall thermal resistance (m² K/W)

\( \text{Res} \)  Swirl Reynolds Number
\( T_{c_i} \) Coolant inlet temperature (K)
\( T_{c_o} \) Coolant exit temperature (K)
\( T_{sat} \) Vapor saturation temperature (K)
\( U_o \) Overall heat-transfer coefficient (W/m\(^2\)·K)

**Greek**

\( \alpha_i \) Inside heat-transfer coefficient (W/m\(^2\)·K)
\( \alpha_{avg} \) Average inside heat-transfer coefficient (W/m\(^2\)·K)
\( \alpha_o \) Outside heat-transfer coefficient (W/m\(^2\)·K)
\( \alpha_{avg} \) Average outside heat-transfer coefficient (W/m\(^2\)·K)
\( \Delta h_v \) Specific enthalpy of vaporization (J/kg)
\( \Delta T \) Temperature rise of coolant across condensing length (K)
\( \lambda \) Thermal conductivity (W/m·K)
\( \Gamma \) Mass flow rate of coolant (kg/s)
\( \rho \) Density (kg/m\(^3\))
\( \eta_{eff-f} \) Fin efficiency
\( \eta \) Dynamic viscosity (N·s/m)
I. INTRODUCTION

A. BACKGROUND

With the advent of more complex shipboard weapons/combat systems and increasing fuel costs, the United States Navy has increasingly recognized a need for an energy-efficient, light-weight, and high-capacity air-conditioning system. Such an advanced system has been proposed and is currently in its test and evaluation phase for the DDG-51 program [Ref. 1].

Among the substantial differences in the advanced air-conditioning plant over extant systems is the use of titanium finned tubes in the condenser, in place of the smooth copper-nickel alloyed tubes previously used. The use of titanium in the air-conditioner's condenser presents two significant advantages. First, since the United States Navy uses ambient seawater as a heat sink, the corrosion resistance of titanium should measurably improve system integrity and reliability. Secondly, the advanced air-conditioning system expects to realize a weight savings per unit of 2286 kg (5040 lbs) and the major portion of this weight savings will come from the use of the lighter-weight titanium condenser tubes [Ref. 1].

Since the early 1970's the United States Navy has used R-114 as its primary refrigerant. The advantages of R-114 over the more-widely-used commercial refrigerants in a naval application derive from its low toxicity, temperature
stability, stability when in contact with moisture, and its applicability to lower-pressure systems [Ref. 1]. R-114\(^1\) will be the refrigerant utilized in the advanced air-conditioning plant.

As no substantial data base on the heat-transfer capacity exists for a system utilizing titanium condenser tube bundles configured as proposed in the advanced air-conditioning plant and consequently, no way exists to measure this design's performance against competing designs, the need arose to develop a test apparatus to provide this data base in order to accurately predict future system performance. The design and subsequent construction of this test apparatus at the Naval Postgraduate School began in 1987 and is documented in the Theses of LCDR David S. Zebrowski [Ref. 2] and of LCDR Thomas J. Murphy [Ref. 3]. The test apparatus was also intended to serve as a test platform for advanced boiling surfaces proposed for use in the advanced air-conditioning plant. The incorporation of the advanced boiling surface test platform and a condenser tube test platform into a single test apparatus allows the widest latitude in examining the effects of various heat inputs, coolant flow rates, and various levels of refrigerant contaminants on individual components and overall system performance. Zebrowski and Murphy constructed

\(^1\)New refrigerants may have to be used in the future due to the "ozone problem."
the basic apparatus, and Murphy operated the system for preliminary evaporator measurements.

B. OBJECTIVES

The major objectives of this thesis were:

1. Refine the design and complete the fabrication of the apparatus for the testing of condenser tube bundles utilizing R-114 as the working fluid.

2. Develop and instrument a data-acquisition system with the associated software to provide a data base on the heat-transfer capacity of the condenser section of the test apparatus.

3. Validate the test apparatus by comparing condenser performance against extant data bases derived from conventional condenser tube bundles.
II. LITERATURE SURVEY

A. GENERAL OBSERVATIONS

Condensation is the phase transformation process in which a vapor is transformed to liquid by removal of latent heat. The promotion of condensation in heat exchangers is used extensively in applications for propulsion engineering and air-conditioning/refrigeration cycles. Due to its importance in the aforementioned fields, considerable research has been directed at the factors influencing the process and ways in which the process can be enhanced. Such factors as various modes of condensation, surface orientation to vapor flow, the shear forces exerted on condensate film, various external and internal surface enhancements, turbulent effects due to cascading condensate flow from another surface, and the effects of fluid properties on the process are detailed extensively in various reviews. This thesis deals exclusively with film condensation of refrigerants on small horizontal tube bundles in a quiescent vapor where tubes with external fins are compared to smooth tubes.

B. SINGLE TUBE INVESTIGATIONS

1. Smooth Horizontal Tube Studies

The first comprehensive condensation model was developed by Nusselt in 1916 [Ref. 4] based on the assumption that a quiescent vapor at saturation temperature coming into
contact with a wall surface below saturation temperature would condense and form a continuous film of condensate growing in thickness as the film flowed off the surface under the influence of gravity. The condensate film at the vapor-liquid interface would be at the vapor saturation temperature with a temperature gradient in the film down to the wall surface temperature. No radiation or convection would take place at the liquid-vapor interface as both liquid and vapor are at the same temperature, however the amount of vapor condensing corresponds to the quantity of heat flowing through the film by thermal conduction. In the case of a horizontal tube, he assumed that condensate flows in a laminar manner around the sides of the tube and off the tube in a continuous sheet. The heat transfer coefficient would be maximum at the top center of the tube decreasing gradually around the surface of the tube, as the inherent thermal resistance in the film grows with the thickness of the film, and eventually goes to zero at tube bottom. Nusselt's model is limited by disregarding surface tension forces that tend to hold up condensate at the tube bottom until overcome by gravity, resulting in the production of condensate droplets rather than a continuous sheet. Nusselt's expression for the average heat transfer coefficient for a single tube subjected to a constant heat flux is given by:

\[ \alpha_o = 0.655 \left[ \frac{\lambda_f^3 \rho_f^2 g \Delta h}{\eta_f \nu_f \cdot D_o \cdot Q} \right]^{1/3} \]  

(2.1)
Although constrained by the aforementioned limitations, Nusselt's model remains the conservative benchmark against which all other models are compared.

2. **Exterior Surface Enhanced Tubes**

Research into ways to improve condensation performance in condensers is motivated by the idea that any force that acts to thin the condensate film promotes an enhancement of heat transfer by minimizing the resistance to heat flow. General enhancement techniques include the fabrication of surfaces that promote dropwise condensation, wrapping exterior surfaces with wire, installation of porous drainage strips, and the fabrication of finned tubes with fins of various geometries and various spacings along the tube. This thesis deals with a low integral-fin tube and its heat transfer enhancement over a smooth tube.

In considering a low integral-fin tube during condensation, there exists two distinguishable regions on the circumference of the tube; a flooded region and an un-flooded region. The flooded portion of the tube defines the condensate retention angle of the tube with respect to the tube circumference. The smaller the condensate retention angle of the tube, the larger the heat transfer capacity of the tube. The fin can be divided into three regions; the fin tips, the sides of the fins, and the fin root area. The majority of heat transfer takes place at the fin tips. Surface tension forces pull the condensate from the tips down
the fin sides into the flooded root area, where gravity drains the condensate to the bottom of the tube. The amount of condensate retained along the circumference of the tube is dependent upon the ratio of surface tension forces to gravity forces.

Beatty and Katz [Ref. 5], in 1948, developed a comprehensive model for the prediction of the heat transfer coefficient of finned tubes based on their experimental results for various test fluids (including R-22) and finned tubes of various metallic compositions, and various fin geometries. Their model assumes gravity-dominated flow and neglects surface tension effects completely. Subsequent experimental results from other sources indicate that the Beatty and Katz model overpredicts the heat transfer coefficient as surface tension increases or as fin density increases. Nevertheless, the Beatty and Katz model conformed to their reported overall heat transfer enhancement of up to 2.3 for R-22 on finned tubes compared to smooth tube data. The Beatty and Katz model is given by:

\[
\frac{\dot{q}}{A_o} = 0.89 \left( \frac{D_f}{D_r} \right)^{1/4} \left( \frac{1}{D_{eq}} \right)^{1/4} \left[ \frac{A_r}{A_{ef}} \right]^{1/4} \left[ \frac{1}{L^{1/4}} \right] \left[ \frac{\rho_f \cdot \eta_f \cdot \Delta T_{ef}}{\gamma_f \cdot g \cdot \Delta h} \right]^{1/4} \]  \tag{2.2}

where,

\[
\left[ \frac{1}{D_{eq}} \right]^{1/4} = \frac{A_r}{A_{ef}} \cdot \frac{1}{L^{1/4}} + 1.30 \left[ \eta_{eff-f} \right] \left[ \frac{A_f}{A_{ef}} \right] \left[ \frac{1}{L^{1/4}} \right] \]  \tag{2.3}
and,

\[ L = \pi \cdot (D_o^2 - D_r^2) / 4 \cdot D_o \]

A three-region theoretical model, based on their experimental results with three rectangular finned tubes, was presented by Karkhu and Borovkov [Ref. 6], in 1971, including surface tension forces. Measured heat-transfer coefficients demonstrated a 50 to 100 percent increase in vapor-side heat transfer coefficients for steam and R-113 condensing on finned tubes compared to smooth tubes. Unfortunately, they did not report enhancements separately for the two fluids. In 1980, results reported by Carnavos [Ref. 7] condensing refrigerants on various finned tubes demonstrated an enhancement of up to 400 percent in the heat transfer coefficient over smooth tube results. Work done by Sauer and Williams [Ref. 8], in 1982, on the condensing performance of finned tubes with oil-contaminated R-113 demonstrated a serious degradation of performance when the surface tension to density ratio was large. The conclusion formed was that the higher-surface-tension oil remained in the fin gaps rendering the finned surface ineffective. Results reported by Honda et al. [Ref. 9], in 1983, condensing R-113 on finned tubes of various geometries showed improvements of 900 percent for the vapor-side heat transfer coefficients at a constant vapor-to-tube-wall temperature difference. The results reported by Kabov
[Ref. 10] in 1984 with refrigerants R-12 and R-21, indicated that the bulk of the latent heat was in fact removed on the lateral fin surfaces and that an optimum fin height and spacing was dependent upon the ratio of surface tension to gravity forces. The results published by Masuda and Rose [Ref. 11] in 1985 in experiments with R-113 condensing on low integral-fin tubes, confirmed that the overall heat transfer coefficient increases, in general, with decreasing fin spacing. Their results showed a 600 percent increase in enhancement over smooth tube performance. More recent results by Marto et al. [Ref. 12] with R-113, demonstrated a 700 percent enhancement in performance over a smooth tube and gave an optimum fin spacing of 0.5 mm for that fluid. Work performed and published in the same time frame by Sukhatme et al. [Ref. 13] with R-11 on conventional integral-fin tubes and special pyramid-shaped fin tubes, reported enhancement ratios of 5 to 7 for the low integral fin tubes and 10.3 to 12.3 for the pyramid-shaped fin tubes.

C. TUBE BUNDLE INVESTIGATIONS

1. Smooth Tube Bundles

In smooth tube bundles, two conflicting factors play a role in determining bundle performance. First, the condensate flowing from the tubes above a given tube in a bundle tends to thicken the condensate film on that tube, hence increasing the resistance to heat transfer. This effect is known as the condensate inundation effect. Secondly,
droplets from other tubes striking the film surface on a tube with a velocity provided by gravity or vapor flow, can create ripples or waves in the condensate film imparting a turbulence within the condensate film that produces an enhancement of heat transfer performance.

In 1949, Jakob [Ref. 14] elaborating on Nusselt's model, predicted that the vapor-side heat transfer coefficient for a tube in a bundle, compared to the first tube in the bundle, was a function of that tube's relative position in the bundle. This model was based upon the assumption that a continuous laminar sheet of condensate flowing off the tube directly above the tube considered and striking the top of this tube further thickened the condensate film on this tube. Jakob's model is given by:

\[
\frac{\alpha_N}{\alpha_1} = N^{-1/4} \tag{2.4}
\]

In 1958, Kern [Ref. 15] proposed a model based on the assumption that discrete droplets or jets of fluid from other tubes caused ripples in the condensate film diminishing the inundation effect. Kern's model is less conservative than Nusselt's and, in many cases, remains the applied industrial design standard. Kern's model is given by:

\[
\frac{\alpha_N}{\alpha_1} = N^{-1/6} \tag{2.5}
\]
Work by Chen [Ref. 16], published in 1961, proposed a model that considered the momentum gain of falling condensate as well as the condensation of vapor on sub-cooled condensate droplets or sheets. Chen's model which is essentially Nusselt's model times a factor that incorporates the phase change number is given by:

\[
\frac{\alpha_N}{\alpha_1} = N^{-1/4}[1 + 2\cdot\text{Ph} \cdot (N-1)]
\] (2.6)

where the Phase Change number is given by:

\[
\text{Ph} = \frac{C_p \Delta T}{\Delta h_v}
\]

Equation (2.6) is valid provided,

\[
\text{Ph} \cdot (N-1) \leq 2.0
\]

A model proposed by Eissenberg [Ref. 17] in 1972, assumes that condensate does not always drain in a vertical direction but may be diverted sideways due to local vapor flow conditions. In this case, the condensate strikes subsequent tubes on their sides rather than on their tops, minimizing inundation effects on the condensate film in the top portion of the tube. Eissenberg's model is given by:

\[
\frac{\alpha_N}{\alpha_1} = .60 + .42 \cdot (N^{-1/4})
\] (2.7)
2. Enhanced Tube Bundles

Katz and Geist [Ref. 18] in 1948, studying six fin tubes in a vertical row, using R-12 among other working fluids, found that the effect of condensate inundation was over-predicted by Jakob's model and proposed that the exponent in Equation (2.4) be changed to 0.06 for finned tubes.

A theoretical model was proposed by Honda et al. [Ref. 19] in work published in 1987, for finned tube bundles that showed good agreement, within 5 to 7%, for data taken condensing acetone and R-12 on finned tubes. Their model relies upon solving a set of algebraic equations describing the vapor-to-coolant conjugate heat transfer problem. A compendium of the aforementioned models, both single tube and bundles, is provided by Marto [Ref. 20].

As of the date of this writing, the author is unaware of any comprehensive model, substantiated by experimental results, that accurately predicts heat transfer performance for enhanced tube bundles with varying fin geometries and varying pitch.
III. EXPERIMENTAL APPARATUS

A. CONDENSER/BOILER TUBE BANK TEST PLATFORM

1. Overview

The composite test platform, with associated support systems, is depicted schematically in Figure 3.1. The boiler/condenser unit was fabricated from 6.35 mm thick, rolled stainless steel plates designed to withstand an absolute pressure of 308 kPa. The top cylinder which serves as the condenser for the apparatus is 1.30 m in length with an external diameter of 0.61 m. The effective condensing length is 1.22 m. The condensing chamber is capped on either end with circular stainless steel plates of 0.71 m diameter and connected to the chamber with a flange and stud assembly. System integrity is maintained with a 3.20 mm thick rubber gasket. The end caps support the nylon block condenser tube mounts, stainless steel backing plates, auxiliary condenser coils (coolant entrance side), and mixing chambers (coolant exit side). The condenser chamber has five 12.7 mm thick Pyrex glass view ports backed with 12.7 mm thick Plexiglas. The view ports are 127 mm in diameter and are located axially along the main chamber, angled so as to provide top to bottom views of the test tubes at various locations along the effective condensing length. The condenser chamber and
Figure 3.1 System Schematic
ancillary equipment are depicted graphically and in photographs in Figures 3.2 through 3.5.

Internal to the condenser chamber, a stainless steel shroud is fitted over the effective condensing length of the instrumented test tubes (see Figure 3.6). The purpose of the shroud is to channel refrigerant vapor along the inside circumference of the shell, collecting vapor at the top, and then forcing vapor through the vertical axis of the instrumented tube bank into the shroud's well, where condensate is collected and the remaining vapor is condensed by an auxiliary condenser. The auxiliary condenser is composed of five helically wound copper tubes of 9.53 mm diameter suspended inside the shroud well by cantilevered rods welded to the entrance end cap. The stainless steel shroud was fabricated with a glass panel serving as one side of its stem to permit viewing of the instrumented tubes through the view ports.

The condenser chamber is attached to the boiler chamber by a rolled stainless-steel cylinder nominally 280 mm in diameter and 203 mm in length, located mid-way along the condenser chamber's length allowing condensate to drain by gravity. A collar dam was fitted at the connecting flange, for the initial purpose of providing a condensate drain point to send condensate to the auxiliary storage unit. Subsequently, a faster, more-efficient method of transferring refrigerant was devised that allowed refrigerant vapor to be
Figure 3.2 Photograph of Apparatus and Support Systems
Figure 3.3 Apparatus Schematic
Figure 3.4 Photograph of Coolant Entrance Endcap

Figure 3.5 Photograph of Coolant Exit Endcap
Figure 3.6 Cross-section of Condensing Chamber Schematic
sent and condensed in the auxiliary storage unit. A 9.53 mm diameter copper tubing was provided for the vapor flow from the top of the condenser chamber to the storage tank. A similar tubing was provided between the storage tank and the boiling chamber to allow liquid flow via gravity.

The boiling chamber is connected to the condenser unit via the interconnecting riser as previously discussed. The boiling chamber was also fabricated from rolled stainless-steel and is cylindrical with an outside diameter of 0.61 m and a length of 0.279 m. The boiling chamber is fitted with two Pyrex view ports, strengthened by Plexiglas plates, for observation during operation. The boiling unit is comprised of three groups of tubes (see Figure 3.3). In the simulation tube bundle, there are five boiling tubes each nominally rated at 1.5 kW and located at the bottom of the boiler unit. In the auxiliary tube bundle, there are four boiling tubes each nominally rated at 4 kW and located two on either side of the instrumented tube bundle. The instrumented tube bundle is located in the lower center of the boiling unit and is comprised of 35 tubes, with ten active tubes rated at one kW each, five instrumented tubes, and 20 dummy tubes. The power provided to these tubes is controlled by three variac controllers located on a console adjacent to the test platform and fed by a 208 volt power supply. The variac controllers are graduated in one percent increments of maximum power for each tube bundle. The exact location of each tube bundle is
apparent in Figures 3.2 through 3.5. It is a unique feature of this test platform that both boiling and condensation phenomena in a closed loop system can be evaluated simultaneously. Details on the design and construction of the basic test platform are available from Zebrowski [Ref. 2] and Murphy [Ref. 3]. Lightoff and securing procedures for the apparatus are listed in Appendix B.

2. Ancillary Systems

Component equipment that support the R-114 tube bundle test platform and are located external to the apparatus include: (1) an R-114 storage and transfer system, (2) a condenser cooling and flow control system, (3) a coolant (62.4% by weight mixture of ethylene glycol and water) sump, and (4) an eight-ton refrigeration unit.

The R-114 storage and transfer system, as previously described, consists of a stainless-steel cylindrical tank 0.350 m in diameter and 0.91 m in length located on a rack above the coolant sump. Transfer of the refrigerant is accomplished by boiling in the main boiling chamber with vapor being sent to the storage tank via 9.53 mm diameter copper tubing located in the top center of the condenser chamber. The vapor is condensed in the storage cylinder by means of a helical copper coil, suspended the length of the cylinder on a cantilevered bar, that is kept cooled by the water-ethylene glycol mixture. Liquid refrigerant can be returned by gravity to the test platform from the bottom of the storage tank.
through a 9.53 mm diameter copper tubing to the boiling chamber. Faster transfer of R-114 liquid was also possible if the system pressure was at or below the atmospheric pressure. Notice that the storage tank experiences an absolute pressure of about 210 kPa.

Coolant and flow control to the test apparatus and ancillary equipment is accomplished by two different flow path systems. Both flow systems are driven by two 0.5 HP constant-speed pumps that take suction on the main coolant sump. The coolant for the test condenser tube bank passes from the pump discharge through 76 mm diameter PVC piping to a Plexiglas header. At the header, flow is split and proceeds through 15.9 mm diameter Tygon flexible tubing to a bank of rotameters. Flow can be controlled by throttling a gate valve located at the entrance to each flow meter. Coolant flow leaves the exit of each flow meter and proceeds to the instrumented condenser tube bank through flexible Tygon tubing. At the exit of the main condenser chamber, coolant leaves each tube and flows through flexible Tygon tubing to individual mixing chambers (Figure 3.7). From the mixing chambers, coolant passes through flexible Tygon tubing to a central Plexiglas header suspended above the test platform, and the collective coolant is piped back to the main sump through 76 mm diameter PVC pipe. Auxiliary coolant flow leaves the pump discharge through PVC piping and proceeds to a two-way ball valve, where the flow is either sent to the
Figure 3.7 Mixing Chamber Schematic
R-114 storage tank and back to the main sump or is sent through PVC pipe to a large rotameter. From the auxiliary flowmeter, coolant enters a central header and is then split to flow to the five auxiliary condenser coils and back to the coolant sump. Flow through each auxiliary condenser coil is controlled by a valve located at the coil inlet. The coolant sump has a 1.81 cubic meter capacity and is constructed of 12.7 mm thick sheets of Plexiglas. The coolant is approximately 62.4% ethylene glycol and 37.6% water (by weight).

The coolant is chilled by an externally-located, 8 ton refrigeration system that continually re-circulates sump coolant with a 0.75 HP pump. The refrigeration system is capable of maintaining a sump temperature between -21 C and ambient temperature.

3. Instrumentation

The coolant temperature r_se is measured by series-connected thermopiles having ten junctions on either end. These thermopiles were fabricated using type-T thermocouple wire. The ends of the thermopiles are inserted in stainless steel wells with copper-plugged tips located at the entrance to each individual condenser tube and at the exit of this tube's mixing chamber. Inlet coolant temperature is measured with type-T thermocouples also located in the entrance wells. Refrigerant liquid and vapor temperatures are measured with
type-T thermocouples inserted in stainless-steel wells at the locations indicated in Figures 3.2 through 3.5.

System pressure is monitored through a calibrated pressure-vacuum gage valid over a range of 30 inches mercury (vacuum) to 30 pounds per square inch (gage pressure).

4. **Tube Bundle Data Acquisition and Reduction**

A Hewlett-Packard 9816A computer was used to control a Hewlett-Packard 3497A Automatic Data Acquisition System, which read the output of the thermopiles and thermocouples. Readings were made in millivolts and were converted to temperature readings in the data reduction program. The channels read by the data acquisition system are listed in Table 3.1.

5. **Tubes Tested**

Two sets of tubes were tested. The first was a smooth copper tube (inside diameter 13.26 mm, outside diameter 15.88 mm) and the second was a low integral-fin copper-nickel tube (inside diameter 10.16 mm, root diameter 14.00 mm, outside diameter 15.88). These two sets of tubes were tested, in bundles and individually, with R-114 and R-113.
### TABLE 3.1

**CHANNEL ASSIGNMENTS ON DATA ACQUISITION SYSTEM**

<table>
<thead>
<tr>
<th>Channel Numbers</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>Vapor Saturation Temperature</td>
</tr>
<tr>
<td>3-4</td>
<td>Liquid Temperature</td>
</tr>
<tr>
<td>5</td>
<td>Inlet Temperature coolant 1st Tube</td>
</tr>
<tr>
<td>6</td>
<td>Inlet Temperature coolant 2nd Tube</td>
</tr>
<tr>
<td>7</td>
<td>Inlet Temperature coolant 3rd Tube</td>
</tr>
<tr>
<td>8</td>
<td>Inlet Temperature coolant 4th Tube</td>
</tr>
<tr>
<td>20</td>
<td>Thermopile 1st Tube</td>
</tr>
<tr>
<td>21</td>
<td>Thermopile 2nd Tube</td>
</tr>
<tr>
<td>22</td>
<td>Thermopile 3rd Tube</td>
</tr>
<tr>
<td>23</td>
<td>Thermopile 4th Tube</td>
</tr>
</tbody>
</table>
IV. SYSTEM OPERATION AND DATA REDUCTION

A. TEST PLAN AND MODIFICATION OF DESIGN FOR CONDENSER TEST APPARATUS

1. Ability to Change Working Fluids

Although envisioned in the original apparatus design by Zebrowski [Ref. 2] and Murphy [Ref. 3], no physical system existed for the change-out and storage of working fluids. The system was designed as a general test platform to evaluate the performance of various refrigerants and steam during condensation on a variety of test tubes.

The R-114 storage and transfer system as described in Chapter III, ancillary systems, was designed and built to allow for the storage of refrigerants that evaporate at atmospheric temperature and pressure. This additional capability not only conserves expensive refrigerants but facilitates speedy change of these working fluids during the evaluation of a particular tube with a variety of refrigerants.

2. Tube Alignment and Reduction of Tubes in Test Bundle

Visual inspection, during preliminary experimental runs, revealed that bowing of the tube bundle was detrimentally affecting condensation patterns. As a result of misalignment of the endcaps during fabrication, bending moments of varying magnitudes and directions resulted in
condensate flow striking subsequent tubes in the vertically-oriented bundle at different positions around the circumference of the tubes. Upon disassembly of the end plates of the apparatus and comparison with the proposed drawings for the DDG-51 refrigeration condenser provided by the David Taylor Research Center, miscalculations in the tube pitch were revealed. The vertical pitch required for the project is 35.74 mm, centerline to centerline. The nylon bundle plates, as manufactured, had a pitch that was considerably less. In an effort to correct the tube misalignment problem, a low-powered laser was proposed to align the bundle tubes. A new nylon endplate was fabricated for the exit endcap, at the correct pitch with the tube bundle reduced to four vertical tubes, due to constraints in the endcap openings. An aluminum mount for the laser was fabricated by machine shop personnel that fit snugly into the tube penetrations of the nylon block. Several test projections were conducted on a plastic template fitted to the entrance endcap to minimize misalignment possibilities. The plastic template was scribed and cut with particular attention paid to correct pitch and used to manufacture the entrance nylon endplate. Subsequent visual inspection during experimental runs revealed that misalignments and bowing had been corrected.
3. **Vapor Superheat Problems**

During initial experimental runs, observed discrepancies in the measured temperature increases across the condenser tube lengths when compared to predicted temperature increases, prompted consideration of the possibility of vapor superheat occurring as vapor (at saturation temperature less than room temperature) flowed from the boiling chamber through the riser and up the sides of the condensing chamber. A two-pronged strategy was developed to minimize this possible effect. First, the apparatus shell was completely insulated with 12.7 mm thick foam insulation and all ancillary tygon tubing was insulated with double-wrapped, 3.18 mm thick foam insulation. Secondly, all experimental runs were performed at vapor saturation temperatures above the ambient temperature.

4. **Contamination Problems**

Visual inspection of the condensing tubes during operation, correlated with observed disparities in measured temperature increases across condenser tubes, revealed a structured, crystalline surface or matrix formation on the tube surfaces that inhibited heat transfer. The first appearance of the inhibiting matrix occurred during runs with smooth copper tubes and with the coolant inlet temperature at approximately -20 C. The working fluid, R-114, was transferred to the storage unit except for an oily residue that remained in the bottom of the boiling chamber. This residue was not analyzed, but was assumed to be machining oil.
that remained after apparatus fabrication. The system was flushed twice, once with acetone and once with R-113, and the boiling chamber was scrubbed out. The smooth copper tubes were re-installed after a complete cleaning of their outside surfaces, and the experimental runs were repeated under the same conditions. Visual inspection again revealed the presence of the matrix formation on the tubes, and the possibility of water contamination in the R-114 was conjectured as a probable cause. The matrix was thought to be ice crystals solidified on the tube surface. The decision was made to continue experimental runs with a different refrigerant (R-113) and a different type of condensing tube (copper-nickel 1024 fpm low integral-fin tube), with the aim of understanding the conditions that caused the phenomena to exist. First, a run was made using R-114 with the copper-nickel finned tube under exactly the same conditions as described in the smooth copper tube runs. Visual inspection, during this run, revealed an apparent thickening of the fins at the top of the tube when compared visually with the second tube (see Figure 4.1(a) fin normal appearance and Figure 4.1(b) fin's thickened appearance). This appearance of thickening gave credence to the belief that water contamination was causing an ice layer to form on the top tube between fins. The refrigerant was then changed to R-113 and the run was repeated, with the inlet cooling temperature at approximately -20 C. Again, a marked thickening of the finned
Figure 4.1 Cross-section of Fin Surface Schematic
surface appeared on the top of the first tube. The next experimental run was conducted on the same finned tube with R-113, but at a coolant inlet temperature slightly above 0 C. In this situation, no visible thickening of the finned surface was observed, but disparities in temperature increases across tube lengths persisted. The run was repeated several days later to observe whether the phenomenon consistently repeated itself. Finally, the smooth copper tube was substituted for the finned tube and the experimental run repeated at the higher coolant inlet temperature. Noticeable surface contamination, having an orange peel appearance, recurred. In addition, during this run, there were indications that a pocket of non-condensable gases formed in the top of the condensing chamber. As every effort had been made to evacuate the apparatus prior to commencing the experimental run, and no evidence exists to support outside leakage of air into the system, the possibility exists that contamination within the system produced the non-condensable gases during boiling.

Two possible sources of the contamination are conjectured. The first is that high temperatures on the heater tubes and poor circulation in the boiling chamber are combining to break down the refrigerant molecules producing some type of hydro-carbon. The second is that a chemical reaction is occurring between the refrigerants and gasket material in the apparatus producing a hydro-carbon. Time and
funding limitations have prevented further investigation of the problem.

5. Summary

The original test plan called for the testing of various enhanced surfaces in a simulated bundle during condensation of R-114. The contamination problem described above, coupled with the time delays inherent in achieving solutions to the other aforementioned encountered problems, severely limited the results of this thesis.

B. DATA REDUCTION

1. Description of Program Capabilities

The computer program, DRP1F, that collects and processes raw data, in conjunction with a Hewlett-Packard computer/data acquisition system described in Chapter II, is listed in its entirety in Appendix C. The program is designed to calculate and plot heat transfer parameters for a variety of different tube bundles, utilizing R-114, R-113, or steam as the working fluid. The program has the added capability of allowing testing for single tube performance. The program consists of five main sections, as follows:

1. Driver Program,
2. Main Program,
3. Property Subroutines,
5. Plotting Subroutines.
Of these five sections, only the modified Wilson Plot subroutine will be described in lengthy detail.

The driver program permits the user to take data, reprocess data, or plot re-processed data through various subroutines. The driver program is listed in lines 1000 through 1125, in Appendix C.

The main subroutine (lines 1130-2315) can be divided into five parts. The first part allows the user to select the physical parameters used in data reduction. The selection of parameters consists of the working fluid to be used (R-114, R-113, or steam), the vapor saturation temperature to be used (derived from averaged thermocouple readings in either the vapor section or liquid region of the apparatus), the instrumented test tube type, and whether data will be taken on a bundle or individual tubes. The second part allows the user to reprocess data with the same selection of physical parameters described above, but calls the modified Wilson Plot subroutine to calculate the inside and outside coefficients used in the correlations. Basic data reduction takes place in the third part (lines 1945-2125). Subroutines are called to calculate the properties of the ethylene glycol-water solution. These properties, with the physical tube dimensions, are used to calculate velocities and Reynolds numbers. Low coolant velocities and high viscosities prompted the use of twisted tape inserts (thickness 0.559 mm, with a pitch for a 180 degree twist of three times the tube's inner
diameter) to increase the inside heat flux. The inside Nusselt number with a twisted tape insert, provided by Hong and Bergles [Ref. 21], is given by the correlation:

\[
\frac{\overline{Nu}}{\overline{D_i}} = 5.172(1 + 5.4838 \cdot 10^{-3} \cdot (Pr^{0.7} \cdot (Re_s^{1.25})^{1/2})
\]  

(4.1)

where the Reynolds number for coolant flow was given by:

\[
Re_s = 4 \cdot \frac{\pi \cdot \eta \cdot (D_i - 4\delta)}{\gamma}
\]  

(4.2)

where, \( \delta \) is tape thickness.

The outside heat transfer coefficient is then given by the well-known summation of resistances to heat transfer:

\[
\frac{1}{U_o A_o} = \frac{1}{\overline{\alpha_o A_o}} + R_f A_o + \frac{1}{\overline{\alpha_i A_i}}
\]  

(4.3)

which algebraically reduces to:

\[
\overline{\alpha_o} = \frac{1}{\frac{1}{U_o A_o - R_m A_o} - R_f A_o - \frac{1}{\overline{\alpha_i A_i}}}
\]  

(4.4)

The heat transferred to the coolant (Q) is given by the relationship:

\[
Q = \dot{\gamma} \cdot C_p \cdot (\Delta T)
\]  

(4.5)
The heat flux (Q") is subsequently calculated by dividing by the outside surface area:

\[ \frac{Q''}{A_o} \]  \hspace{1cm} (4.6)

where \( A_o = \pi D_o \cdot L \). And, the overall heat transfer coefficient \( (U_o) \) is given by:

\[ U_o = \frac{Q''}{\text{LMTD}} \]  \hspace{1cm} (4.7)

where the Log Mean Temperature Difference (LMTD) is defined to be:

\[ \text{LMTD} = \frac{\Delta T}{\log\left[\frac{T_{\text{sat}} - T_{\text{C}}}{T_{\text{sat}} - T_{\text{C}_o}}\right]} \]  \hspace{1cm} (4.8)

It should be noted that the wall resistance due to fouling was assumed to be negligible for the purposes of calculation.

The fourth part of the main subroutine creates a raw data file (lines 1680-1835), allowing subsequent reprocessing by the modified Wilson subroutine. The fifth part of the main subroutine provides a printed output both while taking initial data and subsequently after reprocessing data.

The third major section of the computer program calculates fluid properties through called functions for both the working fluid and the coolant. The calculated coolant
properties as a function of temperature (lines 2330-2615), are
kinematic viscosity, specific heat, density, Prandtl number,
and conductivity.

The fifth major section of the program provides
plotting routines for the output files generated in the
program. The relationships graphically displayed are heat-
transfer coefficient ratios (either based on the first tube in
the bundle or as a ratio of the Nusselt value) plotted against
tube position, heat transfer coefficient plotted against
either the heat flux or temperature rise of the coolant, and
the X-Y plot generated from the modified Wilson Plot results.

2. Modified Wilson Plot

The modified Wilson Plot, as outlined by Marto [Ref.
22], accomplishes an indirect measurement of the outside heat-
transfer coefficient. The implicit assumption is that the
overall heat transfer coefficient \((U_o)\) is reliably known from
data and, therefore a summation of heat transfer resistances
is assumed. This summation relationship is given by:

\[
\frac{1}{U_o} = \frac{1}{\alpha_o} + R_{fi} + R_{m} + \frac{1}{\alpha_i} \left( \frac{A_o^2}{A_i^2} \right) \tag{4.9}
\]

where resistance due to wall fouling is assumed equal to zero.
The summation equation is transformed to a linear
relationship, as follows:

\[
\frac{1}{U_o} - R_{m} = \left( \frac{A_o^2}{A_i^2} \right) \frac{1}{\alpha_i} + \frac{1}{\alpha_o} \tag{4.10}
\]
where:

\[
\overline{\alpha}_i = C_i \left( \frac{\lambda}{D_i} \right) ; \quad \overline{\alpha}_o = C_o F
\]  

which results in the simple linear form, \( Y = mX + b \). It should be noted that Theta (defined in line 3290) is derived from the Hong and Bergles [Ref. 20] relationship for the inside Nusselt number, given by:

\[
\overline{Nu}_i = \frac{\overline{\alpha}_i D_i}{\lambda} = C_i \left[ 1 + 5.4838 \cdot 10^{-3} (Pr^{0.7}) \cdot \left( \frac{Re_s}{y} \right)^{1.25} \right]^{1/2}
\]  

(4.12)

hence,

\[
\varepsilon = \left[ 1 + 5.4838 \cdot 10^{-3} (Pr^{0.7}) \cdot \left( \frac{Re_s}{y} \right)^{1.25} \right]^{1/2}
\]  

(4.13)

Further, \( F \) (defined in line 3330), is derived from Nusselt's relationship for a horizontal cylinder subjected to a constant heat flux [Ref. 4], given by:

\[
\overline{\alpha}_o = 0.655 \left[ \lambda \rho^2 g \Delta h \sqrt{\eta \cdot D_o \cdot Q''} \right]^{1/3}
\]  

(4.14)

Hence,

\[
F = \left[ \lambda \rho^2 g \Delta h \sqrt{\eta \cdot D_o \cdot Q''} \right]^{1/3}
\]  

(4.15)
X and Y values are calculated from raw data and the data are fit with a least squares approximation. Initial assumed values are taken from the aforementioned correlations, and the solutions iterated to find the inside coefficient ($C_i$) and the outside coefficient ($C_o$) that fit the data, where:

\[ Y = \left[ \frac{1}{U_o} - R_m(A_o) \right] F \quad X = \frac{D_o \cdot F}{\lambda} \]  

(4.16)

the slope (m) is given by:

\[ m = \frac{1}{C_i} \]

and the intercept (b) is given by:

\[ b = \frac{1}{C_o} \]

The accuracy of this method relies heavily upon the number of data points taken and the range of velocities utilized.
V. RESULTS AND DISCUSSION

A. EXPERIMENTAL SEQUENCE

The data runs are summarized in Table 5.1 according to tube type, refrigerant used, and approximate operating parameters. Specifics for each run are provided in the following section under the run title.

TABLE 5.1
SEQUENTIAL LISTING OF DATA RUNS

<table>
<thead>
<tr>
<th>Run Title</th>
<th>Tube Type</th>
<th>Refrigerant Used</th>
<th>Coolant T inlet</th>
<th>Vapor T saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMT02</td>
<td>smooth</td>
<td>R-114</td>
<td>-20 C</td>
<td>17.8 C</td>
</tr>
<tr>
<td>CNFT01</td>
<td>finned</td>
<td>R-114</td>
<td>-21 C</td>
<td>18.3 C</td>
</tr>
<tr>
<td>CNFT02</td>
<td>finned</td>
<td>R-113</td>
<td>-21 C</td>
<td>64.4 C</td>
</tr>
<tr>
<td>CNFT03</td>
<td>finned</td>
<td>R-113</td>
<td>-3 to +6 C</td>
<td>52.2 C</td>
</tr>
<tr>
<td>CNFT04</td>
<td>finned</td>
<td>R-113</td>
<td>-3 to +6 C</td>
<td>46.3 C</td>
</tr>
<tr>
<td>SMT03</td>
<td>smooth</td>
<td>R-113</td>
<td>-1 to +6 C</td>
<td>56.7 C</td>
</tr>
</tbody>
</table>

B. EXPERIMENTAL RESULTS

1. Smooth Tubes with R-114 and Low Coolant Temperature

SMT02 was an experimental run made with four smooth copper tubes while condensing R-114. Vapor saturation temperature was 17.8 C. Ambient temperature was 20 C. The ethylene glycol coolant inlet temperature was -20 C. The
experiment was conducted following a cleaning of the boiling chamber, two flushings of the apparatus, once with acetone and once with R-113, evacuation to 27.5 in Hg., and filling the system from an unopened cylinder of R-114. After filling the system, the apparatus pressure stabilized at 17 psig. The system pressure was lowered to 10 psig by opening the coolant flow through the auxiliary condenser. When the desired gage pressure was reached, the lowest flow rate was set through the instrumented tube bundle, and all three heater units were set for power levels corresponding to approximately 10 kW total. Gage pressure was maintained nearly constant by controlling coolant flow through the auxiliary condenser. The system required approximately 35 minutes from lightoff to reach a steady state condition, indicated by nearly constant gage pressure. The R-114 appeared clear at the commencement of the data run. By the time the apparatus reached a steady state condition, the contamination matrix was fully formed and visible on the top two tubes in the bundle. Data were taken at nine different coolant velocities, after the voltage indicator on the data acquisition system for the bottom tube thermopile appeared to reach a fixed value following each velocity change. Data for the tube bundle run (Figure 5.1) clearly demonstrates an observed uncertainty of about 7% in the overall heat transfer coefficient \( (U_o) \) at velocities close to 0.9 m/s. This observed uncertainty, in contrast to the maximum calculated uncertainty of 4.5% (see Appendix A),
Figure 5.1 SMT02--Tube Bundle Performance
indicates the effect of the contamination on the measurement of the overall heat transfer. The most significant result of the contamination is the addition of an un-quantifiable resistance to heat-transfer that has produced heat-transfer coefficients approximately half of those predicted by the Nusselt correlation. Further, it is apparent that during bundle operation, the contamination degrades the performance of the tubes in a graduated manner with the first tube being the most adversely affected and the third tube appearing the least affected.

Upon completion of the bundle run, the flow in all of the instrumented tubes was shut off. Gage pressure was maintained at 10 psig by controlling coolant flow through the auxiliary condenser. The coolant inlet temperature remained approximately -20 C. The apparatus remained in this condition until the tube surfaces appeared to dry off, which took normally about ten minutes. Data were then taken at the same nine flow rates, as for the bundle, but with flow through only one instrumented tube at a time, starting with the top tube. Between velocity changes, approximately 10 minutes was allowed for the temperature changes in the tube to take effect. Data runs were made only after inundation from the previously tested tube was no longer present. The R-114 in the boiling chamber remained visually clear for all single tube runs. Again, as in the bundle data, data from the single tube runs (Figure 5.2) fall within an acceptable uncertainty band.
From the conditions under which these runs were made, it is noteworthy and logical that the effect of the contamination increases in magnitude as a run progresses. The first tube gives the lowest results possibly because of residual contamination from the bundle run. The first and second tubes produced approximately the same results as previously discussed in the bundle run, however the third and fourth tubes gave lower results when operating as single tubes than when operating in a bundle, possibly because condensate inundation that provides a rinsing effect in the bundle operation, is no longer present during single tube operation.

2. **Finned Tubes with R-114 and Low Coolant Temperature**

CNFT01 was an experimental run made with copper-nickel low integral-fin tubes condensing R-114. Vapor saturation temperature was 18.3 C. The ethylene glycol coolant inlet temperature was at -21 C. The experiment commenced following the completion of the SMT02 single tube runs, transfer of the R-114 to the auxiliary storage unit, installation of the copper-nickel finned tubes, evacuation of the apparatus to 27.5 in Hg, and a refill of R-114 from the storage unit. This process took approximately six hours to complete. The same data taking procedure as outlined for the smooth tube runs was followed. The appearance of the R-114 was clear at the commencement of the run. By the time the system reached steady state, a marked thickening of the fin areas on the top tube when compared to the fins of the second tube was apparent.
(see Figure 4.1). The R-114 appeared clear at the end of the bundle run. Data from the bundle run (Figure 5.3) show an increase in the overall heat transfer coefficient of approximately 100% when compared to the bundle results for the smooth tubes SMT02 (Figure 5.1). The coolant velocity differences between the smooth tubes and the finned tubes is due to the smaller inside diameter of the finned tubes at the prescribed mass flow rate. There is no disparity between calculated and observed uncertainties given the calculated uncertainty band, but performance remains approximately half of that expected when compared to the values obtained with the Nusselt correlation and enhancement ratios reported by other investigations. Once again, the first and second tubes demonstrate the greatest degradation in performance due to the contamination. The third and fourth tubes either receive less contamination or derive enhancement from condensate inundation flow. From observations, the unknown contaminant had a higher surface tension than R-114, but to what extent the contaminant kept fin root areas flooded and subsequently negated the enhanced surface effect, remains obscured in the uncertainties of the measurements.

The single tube runs followed the procedures outlined for the single tube runs of the smooth copper tubes. However at the end of each single tube run, a marked thickening of the fin surface at the top of the tube was noticeable. Vapor saturation temperature and coolant inlet temperature were the
Figure 5.3 CHT01-Tube Bundle Performance
same as in the bundle run. Data from the single tube runs (Figure 5.4) demonstrate an enhancement of approximately 76% in the overall heat transfer coefficient when compared to its counterpart in SMT02. The spread in the data is approximately 7% and, given the calculated uncertainty band, appears reasonable. Performance remains lower than expected from existing studies, and clearly the magnitude of the contamination effect increases as each run proceeded.

3. Finned Tubes with R-113 and Low Coolant Temperature

Upon completion of the single tube runs described in CNFT01, R-114 was transferred to the storage unit. The apparatus was drained of residual refrigerant, the system was evacuated to 27.5 in Hg, and filled with freshly distilled R-113 by using apparatus vacuum to promote flow from the R-113 container. After filling, system vacuum was at 11 inches Hg. The system was brought to a gage pressure of 5 psig corresponding to a vapor saturation temperature of 64.4 C. Coolant inlet temperature remained the same as described in CNFT01, -21 C. Vapor saturation temperature was monitored through the system pressure, and controlled by regulating coolant flow through the auxiliary condenser. The same nine data points described previously were taken in accordance with the stated procedure. The appearance of the R-113 at the beginning of the run was clear and clean. Upon the conclusion of the run, however, the R-113 had a slight yellowish tinge. During the run, the same marked thickening of the fin surface
Figure 5.4 CNFT01--Individual Tube Performance
described in CNFT01, and shown schematically in Figure 4.1 occurred on the top tube. The data from the bundle run (Figure 5.5) demonstrates only a slight improvement in the overall heat transfer coefficient when compared to the bundle data for SMT02 (Figure 5.1), and in fact represents an approximate 80% decrease in the overall heat transfer coefficient when compared to the performance of the bundle in CNFT01 (Figure 5.3). In view of the fact that these data were collected after transferring the R-114 to the storage unit and filling with freshly distilled R-113, it can only be assumed that the contamination was freshly created with the R-113 and, in fact is associated with the apparatus. It is also possible, based on these results, to infer the presence of non-condensable gases generated by the contamination, although no indications of non-condensable gases were detected during the run. In view of these facts, the reliability of the calculated values for the overall heat transfer coefficient is extremely doubtful even though data spread falls within the acceptable uncertainty band.

Upon completion of the bundle run, data were taken for each of the tubes individually at the same system conditions described for the bundle run, and in accordance with the procedure described for single tube runs. The appearance of the R-113 at the completion of the single tube runs was slightly-darkened, with a yellow tinge, but otherwise appeared free from any floating contaminants. On each of the single
tube runs, a marked thickening of the fin surface developed in the course of the run. There exists reasonably good agreement between the single tube data (Figure 5.6) and the single tube data from CNFT01 in the calculation of the overall heat transfer coefficient, and no disparity exists between the data spread and the calculated uncertainty band. The apparatus was evacuated for five minutes prior to beginning the single tube runs and if non-condensable gases were present during the bundle run, this explains the improved performance of the tubes during individual runs.

4. Finned Tubes with R-113 and High Coolant Temperature

This data run was made with the same copper-nickel tubes described in CNFT01 and CNFT02. The system was allowed to sit overnight at 11 in Hg, while the sump temperature was brought to an operating range of -3 C to +6 C. No change in the system vacuum over this 12 hour period occurred. The decision to run the system at a higher coolant temperature was motivated by a belief that the contamination of the system was water, and that at the colder coolant temperature, an ice sheath was forming on the tubes inhibiting heat transfer. The appearance of the R-113 before commencement of the bundle run was a medium yellow tinge. The system was brought to a steady state pressure corresponding to a vapor saturation temperature of 52.2 C. Difficulty was encountered in maintaining positive system pressure with the auxiliary condenser operating. The auxiliary condenser was therefore turned off and steady state
Figure 5.6 CNPT02--Individual Tube Performance
was maintained by slight power adjustments to the heating elements in the boiling chamber. Nine sets of data were taken in accordance with the procedure for bundle runs previously described. No observable thickening of fin surfaces during the run occurred. The data from the bundle run (Figure 5.7) shows a slight increase in overall heat transfer coefficient over the bundle results obtained in CNFT02 (Figure 5.5) and this is possibly explained by a decrease in the viscosity of the contaminant when exposed to the warmer tube surface.

Single tube runs were made on each of the tubes, in accordance with procedures outlined previously, at the same coolant inlet temperature as in the bundle run, but at a system pressure corresponding to a vapor saturation temperature of 64.4 C. No change in the appearance of the R-113 was detected. Again no thickening of the fin surfaces was detected. The single tube results (Figure 5.8) demonstrate a corresponding range of values in the overall heat transfer coefficient when compared to the results for single tubes in CNFT02 (Figure 5.6), but is significantly higher than the bundle results. It is possible that non-condensable gases were present in bundle operation, but were eliminated by evacuation prior to single tube data being taken. No indications of non-condensable gases were detected during bundle or single tube operation.
5. **Finned Tubes with R-113 and High Coolant Temperature**

This data run was made in order to see if the results produced in CNFT03 were repeatable. The system operating pressure corresponded to a vapor saturation temperature of 46.3°C, and the coolant inlet temperature remained unchanged from the coolant temperature in CNFT03. Nine data sets were taken in accordance with the bundle run procedures outlined previously. No thickening of fin surfaces during the run was observed. The color of the R-113, at the completion of the run, was amber. The bundle data (Figure 5.9) does demonstrate that the results of CNFT03 were repeatable at least within the calculated uncertainty.

Single tube runs were made in accordance with the procedures discussed previously. Nine data sets were taken on each tube, at the same conditions specified in the bundle run. No thickening of fin surfaces was observed during the runs, and the R-113 color remained amber. There is no major disparity between the single tube results (Figure 5.10), and the single tube results for CNFT03, given the calculated uncertainty band. The single tube results were significantly higher than bundle performance, and the build up of non-condensable gases during bundle operation and evacuation of the apparatus prior to commencing single tube runs is conjectured as a possible explanation. At no time during bundle or single tube operation were indications of non-condensable gases detected.
Figure 5.9--CNFT04--Tube Bundle Performance
Figure 5.10--CFTR04--Individual Tube Performance
6. Smooth Tubes with R-113 and High Coolant Temperature

SMT03 was a data run made on the same aforementioned copper tubes, but with R-113. Vapor saturation temperature was 56.7°C. Coolant inlet temperature ranged between -1°C and +6°C. The experiment was conducted following a test run with R-113 and finned tubes and subsequent replacement of the finned tubes, and evacuation to 11 in Hg. While the tube change was being made, the R-113 remained in the boiling chamber exposed to the atmosphere for a two hour period. The R-113 appeared light amber in color at the commencement of the bundle run. The desired gage pressure was maintained by controlling the boiling chamber heaters through their corresponding variac controllers. The auxiliary condenser was not utilized because the additional coolant flow provided by the auxiliary condenser made it difficult to maintain the desired system pressure. During the data run, the top two instrumented tubes assumed an orange peel textured or dimpled appearance. The R-113 had a darker amber appearance at the completion of the bundle run. Again, data were taken at the same nine coolant flow settings following the procedure outlined previously. Data taken during bundle operation (Figure 5.11), while falling within the acceptable uncertainty bands, clearly demonstrates the presence of non-condensable gases as well the presence of the contamination acting to inhibit the overall heat-transfer performance. The top tube's very poor performance can be attributable to its location in
Figure 5.11--SMT03--Tube Bundle Performance
a pocket of non-condensable gases. And the bundle performance as a whole, when taken in comparison with the performance demonstrated in the bundle run of SMT02, indicates an increased concentration of the contamination and the presence of non-condensable gases.

Upon completion of the bundle run, coolant flow through the instrumented tubes was shut off and gage pressure maintained by controlling flow through the auxiliary condenser. While no coolant flowed through the instrumented tubes, the textured appearance noted during the bundle operation gradually transformed to small droplets on the top two tubes which then coalesced into larger ellipsoid shaped droplets that were held on the tube by surface tension forces. Data was taken on the first two tubes in the bundle following the procedure outlined previously for single tube runs. At the completion of the second run, it was noticed that the top view port flanges were cold to the touch while the bottom view port flanges were warm to the touch. The assumption was therefore made that non-condensable gases had collected in the top of the condensing chamber. Before evacuation of the apparatus could be effected, the pyrex glass in the top center view port cracked. As a result, the apparatus was secured and no further data taken. It should be noted that, prior to the view port breaking, there was no evidence to suggest that the apparatus was other than air tight, so that the source of non-condensable gases was most probably due to their generation.
within the boiling chamber. Data taken in the single tube runs (Figure 5.12) reflects not only the effects of the contamination, but also the effects of the presence of non-condensable gases as well. This data showed the greatest variance between calculated and observed uncertainties in the overall heat transfer coefficient. This data is limited to the performance of only the top two tubes, due to the aforementioned breakage of the view port and the presence of non-condensable gases.

C. SUMMARY OF RESULTS

The comparison between finned and smooth tubes shows an enhancement ratio in the overall heat transfer coefficient for the finned tubes compared to the smooth tubes of approximately 2.0. While this enhancement in the overall heat-transfer coefficient might translate to a vapor-side heat-transfer coefficient enhancement ratio of approximately 4.0 to 4.5, based upon the calculated values for the vapor-side heat-transfer coefficient for the tested smooth tubes when compared against the Nusselt's correlation for smooth horizontal tubes and the reported enhancement ratios from other finned-tube investigations [Refs. 5-13], it is estimated that the effect of the contamination during these tests has been a degradation of up to 50% in the vapor-side heat-transfer coefficient. The contamination has resulted in the promotion of another resistance to heat transfer that has no predictable characteristics and can not be quantified. This contamination
Figure 5.12--SMT03--Individual Tube Performance
must therefore be removed before any quantifiable heat-transfer results can be obtained.
VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Based on the data gathered during this investigation for condensation of refrigerants R-114 and R-113 in the multi-tube apparatus, the following conclusions are reached:

1. The construction of a multi-tube condensation test apparatus begun by Murphy [Ref. 3] and Zebrowski [Ref. 4] has been completed, instrumented and integrated with the various support systems.

2. Data reduction software has been developed that produces high confidence results from experimental readings.

3. Data were collected from condensation experiments with R-114 and R-113 on smooth and finned tubes demonstrating an enhancement ratio of approximately 2.0 in the overall heat transfer coefficient for the finned tubes over the smooth tubes.

4. Serious apparatus internal contamination has degraded the value of the overall heat-transfer beyond acceptable limits, making further data reduction meaningless.

B. RECOMMENDATIONS

Based upon the data gathered during the operation of the multi-tube condensation test apparatus, and the experience gained in construction of this apparatus, the following recommendations are made:

1. Samples should be taken from the R-114 and R-113 used in the experimental runs and a chemical analysis performed on these samples to assist in determining the source of the contamination in the system.

2. Modifications to the apparatus, as dictated by the results of the chemical analysis of the refrigerants, should be made.
3. New flow meters allowing a greater range in coolant velocities should be installed. The greater range in coolant velocities will enhance the accuracy of the modified Wilson plot method in calculating the outside heat-transfer coefficient.

4. The temperature control system for the eight ton refrigeration unit should be re-evaluated to determine if tighter control of sump temperature can be maintained.

5. After appropriate modifications to the apparatus have been made, the smooth tube and finned tube experiments should be repeated and contrasted with the results presented here, in order that baseline tube performance might be established.

6. During operation of the system, flow should be throttled to the coolant supply pumps with the valves on the coolant inlet side. This will increase the pump life and reduce noise in the laboratory space.
APPENDIX A

UNCERTAINTY ANALYSIS

A certain amount of uncertainty exists in any engineering measurement. These uncertainties arise both from known sources, such as calibration and measurement errors from sensing devices, and also unknown sources, such as operator experience and unexpected experimental reactions. The procedure used in this uncertainty analysis is based on the Kline-McClintock [Ref. 21] method. This method assumes that a result $R$ is a function of the variables that contribute to that result. Therefore the uncertainty in a result is a function of the uncertainties in each of the variables. This method is expressed mathematically by:

$$\frac{\delta R}{R} = \left[ \left( \frac{\partial R}{\partial V_1} \frac{\delta V_1}{R} \right)^2 + \left( \frac{\partial R}{\partial V_2} \frac{\delta V_2}{R} \right)^2 + \ldots \right]^{1/2}$$ (A.1)

The measurement of the overall heat transfer coefficient ($U_o$) performed in this thesis is given by:

$$U_o = \frac{Q}{A_o \cdot \Delta T}$$ (A.2)

where the heat transferred ($Q$) is given by:

$$Q = \dot{m} \cdot c_p \cdot (\Delta T)$$ (A.3)
and the Log Mean Temperature Difference (LMTD) is defined as:

\[
\text{LMTD} = \frac{(\Delta T)}{\log\left[\frac{T_{sat} - T_{c_i}}{T_{sat} - T_{c_0}}\right]}
\]  
(A.4)

Therefore the uncertainty in the measurement of the overall heat transfer coefficient \((U_o)\) is given by:

\[
\frac{\delta U}{U_o} = \left[ \frac{\delta T}{C_p} \right] + \left[ \frac{\delta T}{C_p} \right] + \left[ \frac{\delta U}{D_o} \right] + \left[ \frac{\delta LMTD}{LMTD} \right]^{1/2}
\]  
(A.5)

where \(\frac{\delta A_o}{A_o}\) reduces to \(\frac{\delta D_o}{D_o}\), and the uncertainty in the LMTD is given by:

\[
\frac{\delta \text{LMTD}}{\text{LMTD}} = [A^2 + B^2 + C^2]^{1/2}
\]  
(A.6)

where \(A\) is given by the expression:

\[
A = \delta T_{sat} \frac{\Delta T}{(T_{sat} - T_{c_i})(T_{sat} - T_{c_0})} \cdot \frac{1}{\log\left[\frac{T_{sat} - T_{c_i}}{T_{sat} - T_{c_0}}\right]}
\]

where \(B\) is given by the expression:

\[
B = \frac{\delta T_{c_i}}{(T_{sat} - T_{c_i})} \cdot \frac{1}{\log\left[\frac{T_{sat} - T_{c_i}}{T_{sat} - T_{c_0}}\right]}
\]

where \(C\) is given by the expression:
\[ C = \frac{\Delta T_C}{(T_{sat} - T_C)} \cdot \frac{1}{\log\left(\frac{T_{sat} - T_C}{T_{sat} - T_C_0}\right)} \]

It should be noted that the uncertainties for mass flow rate \( (\dot{m}) \) and the coolant temperature rise across the condensing tubes \( (\Delta T) \) were calculated during calibration of the flow meters and thermopiles respectfully. Reference material providing data on thermophysical properties, specifically the specific heat \( (C_p) \), listed no uncertainties associated with the curves for aqueous-ethylene glycol solutions. The composition of the aqueous-ethylene glycol solution by weight percentages was calculated by measurement of the specific gravity and the change in this composition over the experimental period was determined to be negligible and therefore this uncertainty has been ignored.

The uncertainty in the overall heat transfer coefficient represents the maximum uncertainty present from the calibration of the four flow meters and the maximum uncertainty in the calibration of the four thermopiles, regardless of association, and therefore represents a conservative estimate of the uncertainty present in each calculation of the overall heat transfer coefficient \( (U_o) \). This maximum uncertainty was calculated to be 4.5 percent.

The disparity between the calculated uncertainties and the uncertainties observed by the spread in data particularly in the single tube runs, can be accounted for by the as-yet
undetermined chemical or phase reactions generated by the contamination in the system.

The values of the uncertainties in the measured variables that were used to calculate the uncertainty by the Kline-McClintock method are listed in Table A.1.

**TABLE A.1**

**UNCERTAINTY VARIABLES**

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>VALUE</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta T$</td>
<td>0.01</td>
<td>From flow meter calibration data</td>
</tr>
<tr>
<td>$\delta C_p$</td>
<td>0.00</td>
<td>Not available</td>
</tr>
<tr>
<td>$\delta \Delta T$</td>
<td>0.01</td>
<td>From thermopile calibration data</td>
</tr>
<tr>
<td>$\delta D_o$</td>
<td>0.002</td>
<td>From micrometer name plate data</td>
</tr>
<tr>
<td>$\delta LMTD$</td>
<td></td>
<td>Listed below by run title</td>
</tr>
</tbody>
</table>

SMT02 0.005  
CNFT01 0.002  
CNFT02 0.001  
CNFT03 0.003  
CNFT04 0.002  
SMT03 0.017  

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APPENDIX B
LIGHTOFF AND SECURING PROCEDURES

A. SYSTEM LIGHTOFF

1. Push the starter button in the control box for the re-circulation pump. This control box is located on the bulkhead above the re-circulation pump in the outside area adjacent to the refrigeration unit.

2. Turn the switch on the refrigeration unit control panel, located in front of the refrigeration unit to the "auto" position after passing through "on" position.

3. Set the desired temperature on the roughly graduated Fahrenheit scale on the control panel thermostat. It requires approximately four hours to chill the sump 40 degrees C. The thermometer located on the side of the ethylene glycol sump must be monitored to ensure the desired sump temperature is attained and maintained. Slight adjustments in the refrigeration unit thermostat can be expected due to the coarseness of its scale.

4. Energize the heater variacs by switching on the breakers in the breaker panel located in the laboratory space on the bulkhead next to the counter.

5. Set the heater variacs to the desired position, after ensuring that the switch panel for the heater tubes located on the apparatus has all switches in the "on" position. Monitor
apparatus pressure through the pressure gage at the top of the apparatus, ensuring system pressure does not exceed 30 psig.

6. Turn on the pump motors by pushing down on the arm of the appropriate breaker box for the pumps located on the bulkhead next to the ethylene glycol sump. The pumps are marked "auxiliary condenser" and "instrumented tube condenser," respectively. Flow in the auxiliary condensate system can be controlled with the individual gate valves located at the coil penetrations on the apparatus. The auxiliary condenser will produce the fastest adjustments to system pressure if pressure is rising too quickly. Flow through the instrumented tubes can be controlled by the ball valves located at the bottom of the respective flow meter.

7. Throttle down coolant flow to the supply pumps with the valve located before the pump suction. This will increase the pump life and reduce noise in the laboratory space.

B. SECURING PROCEDURES

1. Turn all variacs to the zero position and switch off all breakers in the power panel on the bulkhead.

2. Turn the breakers for the pumps to the off position at the switch boxes near the ethylene glycol sump.

3. If apparatus will not be operated for an extended period, turn the switch on the refrigeration control panel to the "off" position after passing through "on."

4. Allow the re-circulation pump to operate for at least ten minutes after switching off the refrigeration unit to
dissipate any back pressure in the system; then secure the pump.
APPENDIX C

DATA REDUCTION PROGRAM

1000 FILE DRPIF
1010 PURPOSE: This program collects and processes condensation data for the R-114 tube-bundle apparatus.
1015 CREATED: NOVEMBER 2, 1988
1020 UPDATED: NOVEMBER 8, 1988
1025 CHANGE MOD=3 AND USING CALCULATED CI FROM WILSON
1030 BEEP
1035 PRINTER IS 1
1040 PRINT USING "$A "$SELECT OPTION"
1045 PRINT USING "$A "$ TAKING DATA OR REPROCESING PREVIOUS DATA
1050 PRINT USING "$A "$ PLOTTING <US DELTA-T
1055 PRINT USING "$A "$ PLOTTING <US N
1060 PRINT USING "$A "$ PLOTTING WILSON
1065 PRINT USING "$A "$ PURGE FILES
1070 PRINT USING "$A "$ XYREAD
1075 PRINT USING "$A "$ NUSSEL ESTIMATE
1080 PRINTER IS 70!
1085 INPUT Icall
1090 IF Icall=0 THEN CALL Main
1095 IF Icall=1 THEN CALL Plot2
1100 IF Icall=2 THEN CALL Plot1
1105 IF Icall=3 THEN CALL Plot3
1110 IF Icall=4 THEN CALL Purge
1115 IF Icall=5 THEN CALL Xyreac
1120 IF Icall=6 THEN CALL Nusseit
1125 END
1130 SUB Main
1135 COM/ Cz/ C(7)
1140 COM/Pf/ Pf
1145 COM/ Nu/ in.Tsat.Gdp1.Hnus
lact
1160 DIM Fma(8,4),Fm(4),Emf(6),Dp(3),T(b),Ho(31),Gdp(3),Uc(3)
1165 DATA 33.4,20,34.4,34.3,23.5
1170 DATA 41.3,25,41.3,41.6,28.6
1175 DATA 49.1,30,49.2,56,3,23.5
1180 DATA 57.0,35,55.3,55.3,28.8
1185 DATA 64.8,40,62.3,62.7,44.6
1190 DATA 72.7,45,69.2,69.7,48.8
1195 DATA 80.6,50,76.3,76.7,55.2
1200 DATA 88.4,55,83.3,83.8,60.5
1205 DATA 96.3,60,90.2,90.8,65.6
1210 READ Fma(*)
1215 DATA 5.172,5.172,5.172,5.172,5.172
1220 READ Cia(*)
1225 DATA 0.1006691,257.27.94369,76.7345.9295,78.025595.81
1230 DATA -2147486559,6.9768E11,-2.66192E13,3.9407E14
1235 READ Ci(*)
1240 DATA 2.015075,0.014000,0.0000,0.0000,0.0000
DATA 366.0,42.975,0.0,0.0,0.0,0.0,0.0,0.0
DATA 0.0005588,3
READ Coe,*,C1a*,*,*mem*,*,*Delta,*,*Hcd*,**
L=1.2192, Condensing length
Jset=0
BEEP
INPUT "ENTER MONTH, DATE AND TIME (MM DD MM SS)",Cig$
OUTPUT 709,"TC",Dtg$
BEEP
INPUT "SELECT OPTION (0=DAG, 1=FILE)",Im
Ihar=1
BEEP
INPUT "WANT A HARDCOPY PRINTOUT (1=DEF,0=NO)",Ihard
BEEP
INPUT "SELECT (0=R-114.1=STEAM,2=R-113.3=E6)",If$1
Im=1
Isat=2
BEEP
INPUT "SELECT SAT TEMP MODE (0=LG,1=VAP,2=(LG+VAP),2=DEF)",Isat
IF Im=1 THEN PRINTER IS 701
IF I=0 THEN
BEEP
INPUT "GIVE A NAME FOR THE NEW DATA FILE",Files$
CREATE BDAT Files,20
ASSIGN @File TO Files$
BEEP
INPUT "ENTER TUBE CODE",Itube
BEEP
INPUT "ENTER EG CONCENTRATION (WT PERCENT)",Egrat
ENTER 703,Cig$
OUTPUT @File,.Dtg$
OUTPUT @File:.Itube,.Egrat,.Dd1,.Dd2,.Dd3,.Dd4,.Dd5
BEEP
INPUT "SELECT (0=TOP,1=SECOND,....,10=BUNDLE)",Iact
PRINT
PRINT USING "$x","FILE NAME ",.1CA",Files$
PRINT
ELSE
BEEP
INPUT "ENTER NAME OF EXISTING FILE",Files$
BEEP
INPUT "ENTER NUMBER OF DATA SETS STORED",Nsets
Iw=1
BEEP
INPUT "WANT TO CALL WILSON? (1=DEFAULT=YES,0=NO)",Iwil
IF Iwil=1 THEN
BEEP
INPUT "WHICH TUBE (0=TOP,1=SECOND,....,10=BUNDLE)",Iact
CALL Wilson
IF Ihard=1 THEN PRINTER IS 701
PRINT
PRINT USING "$x","FILE NAME ",.1CA",Files$
PRINT
IF Iact=9 THEN
PRINT USING "$x","INSIDE COEFFICIENTS: ",4(.00.3D,2X),.C1a*)
PRINT USING "$x","ALPHAS ",4(1X,M2.3DE,0),.Alp

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aa(*))
1535      ELSE
1540      PRINT USING "10X,""INSIDE COEFFICIENT FOR TUBE ",D,"",DD.D
1545      C= CIA(Cia(Iact))
1550      PRINT USING "10X,""ALPHA FOR TUBE ",D,"",DD.D
1555      ELSE
1560      END IF
1565      ELSE
1570      END IF
1575      ASSIGN @File TO File$
1580      ENTER @File:Dtg$
1585      ENTER @File:Itube,Egret,Od1,Od2,Od3,Od4,Od5
1590      INPUT "ENTER TUBE CODE",Itube
1595      END IF
1600      OUT=1
1605      BEEP
1610      INPUT "WANT TO CREATE AN OUTPUT FILE? (1=DEF=YES, 0=NO)",Iout
1615      IF Iout=1 THEN
1620      BEEP
1625      INPUT "ENTER A NAME FOR OUTPUT FILE",Fout$
1630      CREATE BOAT Fout$
1635      END IF
1640      Do=Doa(Itube)
1645      D=Dia(Itube)
1650      Km=ka(Itube)
1655      Ax=PI*D1^2/4    : Cross-sectional area
1660      Ao=PI*Do*L
1665      Rm=Do*LOG(Do/D1)/(2*km)
1670      IF In=0 THEN
1675      PRINT IS 1
1680      BEEP
1685      PRINT "SET FLOWMETERS READINGS CORRESPONDING TO:";
1690      PRINT "FmA=Jet,l;"%; OF METER 2 AND HIT CONTINUE"
1695      PAUSE
1700      OUTPUT 701:"AR AF0 ALB VRS"
1705      Nend=8       : INCREASE TO 9 IF FIVE TUBES IN BUNDLE
1710      FOR I=0 TO Nend
1715      OUTPUT 703:"AS SA";
1720      Vsum=0
1725      FOR J=1 TO 5
1730      ENTER 709.E
1735      Vsum=Vsum+E
1740      NEXT J
1745      Enf(J)=Vsum/5
1750      NEXT I
1755      OUTPUT 709:"AR AF20 AL23 VRS"
1760      FOR I=0 TO 3
1765      OUTPUT 709:"AS SA";
1770      Vsum=0
1775      FOR J=1 TO 5
1780      ENTER 709.E
1785      Vsum=Vsum+E
1790      NEXT J
1795      WAIT .25
1800      NEXT J

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DATA ANALYSIS

Nend=8
FOR I=0 TO Nend
T(I)=FNTv(Emp(I))
NEXT I
Tvap=(T(0)+T(1)+T(2))/3
Tliq=(T(3)+T(4))/2
Tsat=Tliq
END IF

IF Isat=1 THEN
Tsat=Tvap
END IF

IF Isat=2 THEN
Tsat=(Tvap+Tliq)/2
END IF

FOR I=0 TO 4
Fm(I)=FmAset,Jset,I
NEXT I
Jset=Jset+1
PRINT USING "10X","Data set number = ",D0,Jset
PRINT
Ibeg=0
Iend=3
IF Iact=10 THEN
Ibeg=Iact
Iend=Iact
END IF
FOR I=Ibeg TO Iend
Grad=FNGrad(Enf(I+E));
Delt=ABS(Tp(I)/Grad+10);
TavC=T(I+5)+Delt*.5
Rhoeg=FNhoeg(Tav,Egrat)
Nueg=FNnueg(Tav,Egrat)
Mueg=Nueg+Rhoeg
Cpeg=FNcpeg(Tav,Egrat)
Keg=FNkeg(Tav,Egrat)
Preg=Cpeg*Mueg*deg
Mdot=FNpca(I,T(I+E),Enf(I))
Veg=mdot/(Rhoeg*A)
Reeg=Veg+D1/Nueg
Res=4*mdot/(PI*Mueg*D1-4*Delt)
Qdot=mdot*Cpeg*Delt
Qdp(I)=Qdot/A0
IF I=0 OR I=Iact THEN
Qdpi=Qdp(I)
CALL Nusselt
LMntd=Delt/LOG((Tsat-T(I+5))/(Tsat-T(I+5)-Delt))
Vo(I)=Qdp(I)/LMntd
END IF
IF Reeg<4000 THEN
ELSE
BEEP
PRINT USING "10X,""INCORRECT TURBULENT CORRELATION"
Nueg=.027*Reeg*.8*Preg*.333*Cfeg
END IF
H=Nueg*keg/D;
Holl=1/(1/7011-Dp/(D1*M1)-RM):
IF J=0 OR J=last THEN
PRINT USING "10X,""Mass flow rate = ",M3.3DE:Mdot
PRINT USING "10X,""Inside Tube Dia. (m.) = ",M3.3DE:Dia(tube )

PRINT USING "10X,""180 DEG OVER Dia. (HOD) = ",M3.3DE:Hod
PRINT USING "10X,""inlet temperature = ",M3.3DE:Tem
PRINT USING "10X,""Saturation temp (Deg C) = ",M3.3DE:Tsat
PRINT USING "10X,""DELT Tape Thickness = ",M3.3DE:Delta
PRINT USING "10X,""DELT temp Diff. = ",M3.3DE:Delt
PRINT USING "10X,""Log. Mean temp Diff. = ",M3.3DE:Logmtd
PRINT USING "10X,""Heat flux = ",M3.3DE:Qdot(I)
PRINT USING "10X,""Conductivity E.G. = ",M3.3DE:keg
PRINT USING "10X,""Conductivity Tube Metal = ",M3.3DE:km
PRINT USING "10X,""Frandtl number = ",M3.3DE:Pref
PRINT USING "10X,""Reynolds number = ",M3.3DE:Repp
PRINT USING "10X,""Reynolds number H&B S = ",M3.3DE:Res
PRINT USING "10X,""Inside h.t.c. = ",M3.3DE:Hi
PRINT USING "10X,""Inside NUSULT NO. = ",M3.3DE:Nueg
PRINT USING "10X,""OVERALL h.t.c. (Uo) = ",M3.3DE:Uo(I)

PRINT USING "10X,""Heat flux = ",M3.3DE:Qdot(I)
PRINT USING "10X,""Conductivity Tube Metal = ",M3.3DE:km
PRINT USING "10X,""Frandtl number = ",M3.3DE:Pref
PRINT USING "10X,""Reynolds number = ",M3.3DE:Repp
PRINT USING "10X,""Reynolds number H&B S = ",M3.3DE:Res
PRINT USING "10X,""Inside h.t.c. = ",M3.3DE:Hi
PRINT USING "10X,""Inside NUSULT NO. = ",M3.3DE:Nueg
PRINT USING "10X,""OVERALL h.t.c. (Uo) = ",M3.3DE:Uo(I)
PRINT USING "10X,""Tube FM VEG DELT Uo

PRINT USING "10X,""# (K) (m/s) (K) (W/m^2. k)

ELSE
PRINT USING "10X,""Tube FM VEG DELT Uo

END IF
NEXT I
IF I=0 THEN
I=accept=1
BEEP
INPUT "OK TO ACCEPT THIS SET (1=DEFAUT=1, 0=NO)?",I=accept
IF I=accept=1 THEN OUTPUT @File,Fm(1),Em(1),Tp(1)
END IF
IF (I=accept=1 OR I=1) AND Iout=1 THEN
FOR I=2 TO 3
OUTPUT @File,Fm(1),Em(1),Tp(I)
NEXT I
END IF
IF I=0 THEN
I=accept=1
BEEP
INPUT "WILL THERE BE ANOTHER RUN (1=YES=DEFAULT, 0=NO)?",I=accept
IF I=accept=1 THEN 1560
ELSE
IF Jset=Nsets THEN 1600
END IF
ASSIGN @File TO *
IF Iout=1 THEN ASSIGN @File to *  
SUBEND  
DEF GNGrad(T)  
Graa=-3.877857E-5-2*4.7142657E-6*T  
RETURN Graa  
FNEND  
DEF FNCCu(T)  
OFHC COPPER 250 to 300 K  
T1=T+272.15  
K=434.112*Tk  
RETURN K  
FNEND  
DEF FNNeg(T,Egr)  
RANGE OF VALIDITY: -20 to 20 DEG C  
Tk=Tc+273.15  
Num=7.119597E-3-Tk*(7.4863347E-5-Tk*(2.6294943E-7-Tk*3.0833329E-10))  
Num2=4.923759E-3-Tk*(4.9213912E-5-Tk*(1.6437534E-7-Tk*1.833331E-10))  
Num3=8.6568293E-3-Tk*(8.637902E-5-Tk*(3.045032E-7-Tk*3.499996E-10))  
A2=(Num3-2*Num2+Num1)/200  
A1=(Num2-Num1-94*A2)/10  
A0=Num1-42*A1-176*A2  
Nu=A0+Egr*(A1+Egr*A2)  
RETURN Nu  
FNEND  
DEF FNCseg(T,Egr)  
RANGE OF VALIDITY: 0 to 20 DEG C  
Tk=Tc+273.15  
Cp=1.4748125E+3+Tk*6.25  
Cp2=9.5800500E+2+Tk*7.3  
A2=(Cp2-2*Cp2+Cp1)/200  
A1=(Cp2-Cp1-900*A2)/10  
A0=Cp1-40*A1-160*A2  
Cp=A0+Egr*(A1+Egr*A2)  
RETURN Cp  
FNEND  
DEF FNCrhoeg(T,Egr)  
RANGE OF VALIDITY: 0 to 20 DEG C  
Tk=Tc+273.15  
Ro=1.060875E-3-Tk*(4.0831837E-1+Tk*(2.6294943E-7-Tk*3.0833329E-10))  
Ro3=1.0885934E+3-Tk*(3.397559E-1+Tk*(4.9213912E-5-Tk*1.833331E-10))  
A2=(Ro3-2*Ro2+Ro1)/200  
A1=(Ro2-Ro1-900*A2)/10  
A0=Ro1-40*A1-160*A2  
Ro=A0+Egr*(A1+Egr*A2)  
RETURN Ro  
FNEND  
DEF FNPrreg(T,Egr)  
Pr=FNCseg(T,Egr)*FNNeg(T,Egr)*FNCseg(T,Egr).*FNPreg(T,Egr)  
RETURN Pr  
FNEND  
DEF FNKeg(T,Egr)  
RANGE OF VALIDITY: -20 to 20 DEG C  
Tk=Tc+273.15  
K1=2.2824708E-1+Tk*(5.999286E-4+Tk*3.877857E-5)  
K2=2.544651E-1+Tk*(2.397559E-4+Tk*7.142857E-5)  
K3=3.1309332E-1+Tk*(3.8042657E-4+Tk*1.4285714E-5)  
A2=(K2-2*K1+K)/200  
A1=(K2-K1+900*A2)/10  
A0=-(40*A1-1600*A2)  
K=A0+Egr*(A1+Egr*A2)  
RETURN K
RETURN Tanr
2640 DEF FN_Tann(I)
2645 P=Exp(-I)
2650 DEF FN_Tann(I) =
2655 COM(Ce(.77)
2660 T=C(I)
2665 FOR I=1 TO n
2670 T=T+C(I)*U
2675 NEXT I
2680 RETURN T
2685 FNEND
2690 DEF FNBeta(T)
2700 P=NHro(T)
2705 Rm=NHro(T-1)
2710 Beta=2*(P/Rm)**(P/Rm)**.2
2715 RETURN Beta
2720 DEF FNPset(Tc)
2725 IF TO 50 deg F CURVE FIT OF Pset
2730 Tf=1.8*Tc+32
2735 Pset=5.945555+Tf*(1.15362082+Tf*(1.48409633*7-Tf*9.61567116-6))
2740 Pg=Fa-14.7
2745 IF Pg>0 THEN 1+*PSIG,-*in Hg
2750 Pset=Pf
2755 ELSE
2760 Pset=Pf*29.92/14.7
2765 END IF
2770 RETURN Pset
2780 FNEND
2790 DEF FNMcal(I,T,Fm)
2800 DIM B1(4),B2(4),B3(4),M1(4),M2(4),M3(4)
2805 DATA 7.48835E-3,-6.71749E-3,-5.8103E-3,-5.5279E-3,4.125E-4
2810 DATA 1.47621E-2,2.63207E-3,-2.76396E-3,-4.30913E-3,-2.1927E-3
2815 DATA 1.048E-3,1.01287E-2,1.114E-2,-3.6877E-3,0.0
2820 DATA 1.71625E-3,2.70418E-3,1.93749E-3,1.50227E-2,2.56645E-2
2825 DATA 2.03462E-3,2.66718E-3,2.95179E-3,2.12453E-3,2.9212E-3
2830 DATA 1.7581E-3,2.70622E-3,2.0012E-3,2.0840E-3,0.0
2835 READ B1(1),B2(1),B3(1),M1(1),M2(1),M3(1)
2840 IF T-7 THEN
2845 Z1=61.1+M1(I)*Fm
2850 Z2=61.1+M2(I)*Fm
2855 S=(Z2-Z1)/13
2860 C=Z1+5*20
2865 ELSE
2870 Z1=61.1+M2(I)*Fm
2875 Z2=61.1+M3(I)*Fm
2880 S=(Z2-Z1)/16
2885 C=Z1+5*7
2890 END IF
2895 Mdot=C*S*T
2900 RETURN Mdot
2905 FNEND
2910 SUB Xyread
2915 BEEP
INPUT "ENTER FILE NAME",F:ile$ 
BEEP 
INPUT "ENTER NUMBER OF X,Y PAIRS",N 
ASSIGN @File TO File$ 
FOR I=1 TO N 
ENTER @File.X,Y 
PRINT X,Y 
NEXT I 
SUBEND 
SUB Purge 
BEEP 
INPUT "ENTER FILE NAME TO BE DELETED",File$ 
PURGE File$ 
GCTC 2810 
SUBEND 
SUB Wilson 
COM /w1/ Doma(4),Dia(4),Kma(4),lact 
COM /w2/ Delta,Isat,Naets,Mod,Dia(3),Alpaa(3) 
DIM Fm(4),Emf(6),T(3),Ya(20),Ya(20) 
BEEP 
INPUT "PLEASE RE-ENTER NAME OF FILE",File$ 
ASSIGN @File TO File$ 
INPUT "ENTER TUBE CODE",;tube 
BEEP 
INPUT "GIVE A NAME FOR XY FILE",;xy$ 
CREATE BOAT ;xy$,5 
ASSIGN ;xy TO ;xy$ 
L=1.2192 
D0=Do(4);tube 
Di=Dia(4);tube 
Km=Kma(4);tube 
A=PI*D0/2/4 ; Cross-sectional area 
Amp=PI*Co*L 
R=Do*LOG(D0/D1)/(2*Km) 

;L=0.0 
Tf=Tsat 
A1a=665 
C1=E.172 
G=5.6 
;eg=0 
;eg=0 
Iend=Z ;CHANGE TO 4. IF FIVE TUBES IN BUNDLE 
IF Iact<1.0 THEN 
Ibeg=Iact 
Iend=Iact 
ENC IF 
FOR I=Ibeg TO Iend 
S=0 
Sy=0 
Sx=0 
Sy=0 
Sset=0 
ASSIGN @File TO File$ 
ENTER @File.Ctg$;tube,Egret,Dd1,Dd2,Dd3,Dd4,Dd5 
ENTER @File.Fm(4),Emf(4),T(3) 
FOR J=0 TO 6 
T(J)=NIVSV(Emf/J)) 
NEXT J 
Tvep=(T(0)+T(1)+T(2))/2
```plaintext
// Code snippet
```
24~5SE:EF
PPIN-EP
1:
Z4ES
Pm
NT
C
CI C. A.FFA=
1
p
',49S
Alpaa
I =Al~ac
CRINTEF
IS
701
3505 OP
J=O
TO Nsets-1
3510
OUTPUT @xy,xeY, ye(J)
3515
NEXT J
3520
PRINTER IS 1
3525
NEXT I
3530
ASSIGN @xy, TO *
3535
SUBENC
3540
SUB Nusselt
3545
COMM /Nus: 1.n, Tsat, Qd.p, hoc
3550
Do=.0180
3555
Ho=1020
3560
IF i=2 THEN
3565
BEEP
3570
INPUT "ENTER TEST AND HEAT FLUX", Tsat, Qdc
3575
END IF
3580
Hfo=FNHf(t);Tsat
3585
Toc=Tsat-Dp/Qd
3590
Tf=Tsat/3+2*T0/3
3595
k=FN(F)
3600
Rhoc=FN(z)(Ff)
3605
Muf=FNz(Ff)
3610
Hoc=BS5*(k*3+Rhoc)*9.81+Hf(1/2(Fo*Do*(Qd)))*.33333
3615
IF ABS((Ho-Hoc)/Hoc)<.001 THEN
3620
Ho=(Ho+Hoc)*.5
3625
GOTO 3585
3630
END IF
3635
IF i=0 THEN PRINT "HO=';Hoc
3640
SUBEND
3645
SUB Plct
3650
DIM yeY(4)
3655
PRINTER IS 705
3660
Idv=1
3665
BEEP
3670
INPUT "OK TO USE DEFAULT VALUES (1=DEF=Y, 0=N)" , Idv
3675
IF Idv=1 THEN
3680
Itn=2
3685
Xmin=1
3690
Xmax=5
3695
Xstep=1
3700
Ymin=0
3705
Ymax=2.0
3710
Ystep=.5
3715
ELSE
3720
INPUT "ENTER MINIMUM AND MAXIMUM X-VALUES", Xmin, Xmax
3725
BEEP
3730
INPUT "ENTER MINIMUM AND MAXIMUM Y-VALUES", Ymin, Ymax
3735
BEEP
3740
INPUT "ENTER STEP SIZE FOR X-AXIS", Xstep
3745
BEEP
3750
INPUT "ENTER STEP SIZE FOR Y-AXIS", Ystep
END IF
PRINT "IN-SPI-ic 2300,1600,6300,6600.,"
PRINT "ES 0,100,0,100,.Tl ",'c.,'
Sfx=1000-X=x--Xmin,
Sfy=100/(Xmax-Xmin)
PRINT "PA 0,0 PD"
FOR Xa=Xmin TO Xmax STEP Xstep
X=Xa-Xmin+Sfx
PRINT "PA,x",',X,",",XT"
NEXT Xa
PRINT "PA 0,0,PU."
PRINT "PA 0,0 PD"
FOR Ya=Ymin TO Ymax STEP Ystep
Y=Ya-Ymin+Sfy
PRINT "PA,0,y",',Y,"YT"
NEXT Ya
PRINT "PA 0,0,PU."
PRINT "PA 0,-10 SR 1,5,2."
FOR Xa=Xmin TO Xmax STEP Xstep
X=Xa-Xmin+Sfx
PRINT "PA,x",',X,",",XT"
NEXT Xa
PRINT "PA 0,0,PU."
PRINT "PA 0,-10 SR 1,5,2."
FOR Ya=Ymin TO Ymax STEP Ystep
Y=Ya-Ymin+Sfy
PRINT "PA,0,y",',Y,"YT"
NEXT Ya
INPUT "ENTER X-LABEL" ,Xlabel$
BEEP
INPUT "ENTER Y-LABEL" ,Ylabel$
BEEP
INPUT "WANT TO PLOT DATA FROM A FILE (1=DEF=Y,0=N)?",Okb
IF Okb=1 THEN
    IF Ism=1 THEN Ylabel$="HN/H1"
    ELSE Xlabel$="Tube Number"
    ELSE
        IF Ism=1 THEN Ylabels="HN/H1"
        ELSE Xlabels="HN/avg/H1"
        ELSE Xlabel$="Tube Number"
    END IF
BEEP
INPUT "ENTER X-LABEL" ,Xlabel$
BEEP
INPUT "ENTER Y-LABEL" ,Ylabel$
END IF
PRINT "SR 1,5,2.PU PA 50,-10 CP","-LEN(xlabels$)/2;"0:LB':xlabels$;"'
PRINT "PA -11,50 CP 0," ;"-LEN(ylabels$)/2*5/6;"0,1:LB':ylabels$;"'
PRINT "CP 0,0 Di"
BEEP
4055 INPUT "ENTER THE NAME OF THE DATA FILE", Dfilename
4060 ASSIGN Dfilename TO Dfilename
4065 BEEP
4070 INPUT "ENTER THE BEGINNING RUN NUMBER", Nd
4080 BEEP
4085 INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED", Nsets
4090 BEEP
4095 INPUT "SELECT A SYMBOL FOR THE PLOTTER (1=*, 2=., 3=c, 4=°, 5='' , 6=', 7), PRINT "PU", "DI"
4100 IF Sy=1 THEN PRINT "SM*"
4105 IF Sy=2 THEN PRINT "SM+"
4110 IF Sy=3 THEN PRINT "SMc"
4115 IF Sy=4 THEN PRINT "SMo"
4120 IF Sy=5 THEN PRINT "SM""'
4125 FOR J=1 TO Nsets
4130 FOR J=0 TO 3
4135 ENTER Dfilename; Ya(J), O
4140 IF J=0 THEN Ytop=Ya(J)
4145 Ya(J)=Ya(J)/Ytop
4150 NEXT J
4155 FOR J=0 TO 3
4160 X=(J-1)*Xmin*Sf,
4165 Y=(Ya(J)-Ymin)*Sfy
4170 PRINT "PA", X, Y, "Pf"
4175 NEXT J
4180 NEXT I
4185 BEEP
4190 ASSIGN Dfilename TO *
4200 GOTO 4040
4205 END IF
4210 BEEP
4215 INPUT "LIKE TO PLOT THE NUSSELT RELATION (1=y, 0=n)?", Onus
4220 PRINT "PU", "SM"
4225 IF Onus=1 THEN
4230 FOR Xa=Xmin TO Xmax, STEP Xstep/50
4235 X=(Xa-Xmin)*Sfx
4240 IF Ism=1 AND Xa>Xmin THEN Yae=(Yae-.75*(Ya-1)/.75)
4245 IF Ism=2 AND Xa>Xmin THEN Yae=(Yae+-.25)
4250 IF Xa<Xmin THEN Yae=1
4255 Y=(Ya-Ymin)*Sfy
4260 PRINT "PA", X, Y, "PO"
4265 NEXT Xa
4270 BEEP
4275 PRINT "PU"
4280 INPUT "MOVE THE PEN TO LABEL THE NUSSELT LINE", Ok
4285 PRINT "LBNusselt"
4290 END IF
4295 IF Ism=2 THEN
4300 BEEP
4305 INPUT "LIKE TO PLOT EXPTL CURVE (1=y, 0=n)?", Okex
4310 Nq=0
4315 IF Okex=1 THEN
4320 BEEP
4325 INPUT "ENTER THE EXPONENT", Ex
4330 FOR Xa=Xmin TO Xmax, STEP Xstep/10
4335 Nq=Nq+1
4340 Yae=Ya"(-Ex)
4345 X=(Xa-Xmin)*Sfx
4350 Y=(Ya-Ymin)*Sfy
4259    IF N=MOD 2=0 THEN
4260        PRINT "PA",X,Y,"PD"
4261    ELSE
4262        PRINT "PA",X,Y,"FU"
4263    END IF
4264
4265    PRINT "FA"
4266    BEEP
4267    INPUT "MOVE PEN TO LABEL AND HIT ENTER",0
4268    PRINT "LE=0"
4269    PRINT "PR-1.0"
4270    PRINT "LE",EX,
4271    GOTO 4300
4272
4273    END IF
4274    GOTO 4510
4275
4276    END IF
4277
4278    IF 0=1 THEN
4279        FOR x=xmin TO xmax STEP 0.04
4280            y=ymin+(-1.5)
4281            x=x-xmin*fy
4282            y=y-ymin*fy
4283        END IF
4284    NEXT x
4285    PRINT "PU"
4286    BEEP
4287    INPUT "MOVE THE PEN TO LABEL KERN RELATIONSHIP",0
4288    PRINT "LEKern:PU"
4289    END IF
4290    PRINT "PA 0,0"
4291    BEEP
4292    INPUT "LIKE TO PLOT EISSENBERG RELATION (1=x,0=n)?",0
4293    IF 0=1 THEN
4294        FOR x=xmin TO xmax STEP 0.04
4295            y=ymin+(-1.5)
4296            x=x-xmin*fy
4297        END IF
4298    NEXT x
4299    PRINT "PU"
4300    BEEP
4301    INPUT "MOVE THE PEN TO LABEL THE EISSENBERG LINE",0
4302    PRINT "LBEissenberg:Pu"
4303    END IF
4304    PRINT "PU SP0"
4305    SUBEND
4306    DEF FNpult(Tc)
4307    COM /Fid/ Ift
4308    DIM K(8)
4309    IF Ift=0 THEN
4310        BEEP
4311        PRINT "PVST CORRELATION NOT AVAILABLE FOR R-114"
4312    STOP
4313    END IF
4314    IF Ift=1 THEN
4315        DATA -7.691234564,-26.08023696,-168.1706546,-64.23285504,-11.964E96
4316        DATA -7.691234564,-26.08023696,-168.1706546,-64.23285504,-11.964E96
4317        PEAD K(8)
4318
4319
4320
4321
4322
4650 \( T = (T_c + 273.15) / 647.3 \)
4655 \( \text{Sum} = 0 \)
4660 FOR \( N = 0 \) TO 4
4665 \( \text{Sum} = \text{Sum} + K(N) \times (1 - T)^{(N+1)} \)
4670 NEXT \( N \)
4675 \( B_r = \text{Sum} / \left( T_x (1 + K(5) \times (1 - T) \times (1 - T)^2) - (1 - T) / (K(7) \times (1 - T)^2 + K(8)) \right) \)
4680 \( P_r = \text{EXP}(B_r) \)
4685 \( P = 22120000 \times P_r \)
4690 END IF
4695 IF \( Ift = 2 \) THEN
4700 \( T_f = T_c + 1.8 + 32 + 459.6 \)
4705 \( P = 10^\left(33.00555 - 4330.98 / T_f - 9.2635 \times \text{LG}(T_f) + 2.0539E-3 \times T_f \right) \)
4710 END IF
4715 IF \( Ift = 3 \) THEN
4720 \( A = 9.394695 - 3066.1 / (T_c + 273.15) \)
4725 \( P = 133.32 + 10 \times A \)
4730 END IF
4735 END IF
4740 RETURN \( P \)
4745 FNEND
4750 DEF \( \text{FNHfg}(T) \)
4755 COM /Fld/ Ift
4760 IF \( Ift = 0 \) THEN
4765 \( T_f = T + 1.8 + 32 \)
4770 \( \text{Hfg} = 1.14515865 + T_f \times (6.951079E-2 + T_f \times 1.3988566E-4 + 1.9607843E-7 \times T_f) \)
4775 \( \text{Hfg} = \text{Hfg} \times 2326 \)
4780 END IF
4785 IF \( Ift = 1 \) THEN
4790 \( \text{Hfg} = 2477200 - 2450 \times (T - 10) \)
4795 END IF
4800 IF \( Ift = 2 \) THEN
4805 \( T_f = T + 1.8 + 32 \)
4810 \( \text{Hfg} = 7.0557857E + 1 - T_f \times (4.030852E-2 + 1.2619048E-4 \times T_f) \)
4815 \( \text{Hfg} = \text{Hfg} \times 2326 \)
4820 END IF
4825 IF \( Ift = 3 \) THEN
4830 \( T_k = T - 273.15 \)
4835 \( \text{Hfg} = 1.35264E + 6 - T_k \times (6.38263E + 2 + T_k \times .747462) \)
4840 END IF
4845 RETURN \( \text{Hfg} \)
4850 FNEND
4855 DEF \( \text{FNMu}(T) \)
4860 COM /Fld/ Ift
4865 IF \( Ift = 0 \) THEN
4870 \( T_k = T - 273.15 \)
4875 \( \text{Mu} = \text{EXP}(-4.4636 + 101.147 / T_k) \times 1.4 \times 10^{-3} \)
4880 END IF
4885 IF \( Ift = 1 \) THEN
4890 \( A = 247.8 / (T + 133.15) \)
4895 \( \text{Mu} = 2.4E-5 \times 10^A \)
4900 END IF
4905 IF \( Ift = 2 \) THEN
4910 \( \text{Mu} = 8.9629819E-4 \times \left( 1.1094609E-5 - T \times 5.566929E-8 \right) \)
4915 END IF
4920 IF \( Ift = 3 \) THEN
4925 \( T_k = 1 / (T + 273.15) \)
4930 \( \text{Mu} = \text{EXP}(-11.0179 + T_k \times (1.744E + 3 - T_k \times (2.80335E + 5 - T_k \times 1.1266E + 8))) \)
4935 END IF
4940 RETURN \( \text{Mu} \)
4945 FNEND
DEF FNVst(Tt)
COM /Fla/ Ift
IF Ift=0 THEN
  BEEP
  PRINT "VUST CORRELATION NOT AVAILABLE FOR R-114"
STOP
END IF

IF Ift=1 THEN
  P=FNPvst(Tt)
  T=Tt+273.15
  x=1500/T
  F1=1/(1+T*1.E-4)
  F2=(1-EXP(-X))"2.5*EXP(X)/X*.5
  B=.0015*F1-.000942*F2-.0004882*X
  K=2*P/(461.52*T)
  V=(1+(1+2*B*K)^*.5)/K
END IF

IF Ift=2 THEN
  IF Ift=0 THEN
    Tk=Tt+273.15
    Cps=4.0118+Tk*(1.65007E-3+Tk*(1.51494E-6-Tk*6.67853E-10))
  END IF
END IF

IF Ift=3 THEN
  IF Ift=0 THEN
    Tk=Tt+273.15
    X=1-(1.8*Tk/753.95)
    Ro=36.3261.146414*X"(1/3)+16.418015*X+17.476836*X".5+1.19828*X"2
  END IF
END IF

RETURN V
FNEND

DEF FNCp(T)
COM /Fid/ Ift
IF Ift=0 THEN
  Tk=Tt+273.15
  Cps=4.21120658-T*2.26826E-3-T*(4.42361E-6+2.71426E-7*T)
END IF

IF Ift=1 THEN
  Cps=2.5567273E-1-T*(9.3400433E-4+1.7207792E-6*T)
END IF

IF Ift=2 THEN
  Cps=3.1860*(1.6084E-2+Tk*(3.35083E-3-Tk*(7.224E-6-Tk*7.61748E-9)))
END IF

RETURN Cps*1000
FNEND

DEF FNRho(T)
COM /Fid/ Ift
IF Ift=0 THEN
  T=Tt+273.15
  X=1-(1.8*Tk/753.95)
  Ro=36.3261.146414*X"(1/3)+16.418015*X+17.476836*X".5+1.19828*X"2
  Ro)=Ro+.062428
END IF

IF Ift=1 THEN
  Ro=999.52946*T*(.01269-T*(5.462513E-3-T*.234147E-5))
END IF

IF Ift=2 THEN

\( R_o = 1.6207479E+2 \times (2.2186346 \times T + 2.3576291E-3) \)

IF \( i = 1 \) THEN
\[ f = 273.15 - 338.15 \]
\[ R_o = 9.24846E-4 \times T + 5.2736E-7 \times T^2 + 5.2444E-10 \times T^3 + 3.057E-12 \]
\[ f = 1/v \]
END IF
RETURN \( R_o \)
DEF FNP(T)
\( P = F N M u(T) \times F N K(T) \)
RETURN \( P \)
DEF FNK(T)
\( \text{COM /Fld/ \( I_f \)} \)
IF \( I_f = 0 \) THEN \( k = 0.071 - 0.000261 \times T \)
IF \( I_f = 1 \) THEN
\[ k = 0.23247 \times \{ 0.8395 \times (1.8007 - \times 0.52577 - 0.07344 \times T) \} \]
END IF
IF \( I_f = 2 \) THEN
\( Y = 0.2095239E-2 \times T \times (2.221428E-4 \times T + 2.3009524E-6 - 0.952) \)
END IF
IF \( I_f = 3 \) THEN
\( T = T + 273.15 \)
END IF
RETURN \( k \)
DEF FNM(T)
\( \text{COM /Fld/ \( I_f \)} \)
IF \( I_f = 1 \) THEN
\( k = 4.203849E-7 \times (5.88132E-4 \times T + 4.5660317E-6) \)
END IF
IF \( I_f = 2 \) THEN
\( f = 1.8 - 32 \)
\( f = 4.27887E+7 \times f \times 0.94E78E-7 \times f \times 1.221A8E-4 \)
\( f = 0.23256 \)
END IF
IF \( I_f = 3 \) THEN
\( f = 150 \) TO BE VERIFIED
END IF
RETURN \( f \times 1000 \)
DEF PNP(T)
\( \text{COM /Dr1/ Star, Sym, Icon} \)
\( \text{COM /Fld/ \( I_f \)} \)
DIM \( C(9), X(a(7)), D(a(3)) \)
DATA 0.0156, 0.0156, 0.0156, 0.0156
READ \( D(a(*)) \)
F = 1
PRINT IS 1
BEEP
PRINT USING "4X," "Select Option X-Y Limits.""
PRINT USING "Ex," "0 Use default values"
PRINT USING "El,"": Use new values.

INPUT Crd

BEEP

INPUT "ENTER TUBE CODE": Icode

Do=Cde: ltube;

Int=2

BEEP

PRINT USING "4X,"": Select option ""

PRINT USING "5X,"": 0 h versus c ""

PRINT USING "6X,"": I q versus Delta-T ""

PRINT USING "EX,"": 2 h versus Delta-T (default)"

INPUT Int

PRINT IF 705

IF Ox==0 THEN 'AXIS DEFAULT VALUES

IF Int=0 THEN '(h vs q)

Ymin=0

Ymax=60

Ystep=10

Xmin=.2

Xmax=1.4

Xstep=.2

END IF

IF Int=1 THEN '(q vs t)

Xmin=0

Ymin=.5

Xmax=15

Xstep=3

Ystep=1

END IF

IF Int=2 THEN '(h vs t)

Xmin=0

Ymin=0

Xmax=50

Ymax=6

Xstep=10

Ystep=1

END IF

END IF

IF Ox==1 THEN

BEEP

INPUT "ENTER MINIMUM AND MAXIMUM X-VALUES": Xmin,Xmax

BEEP

INPUT "ENTER MINIMUM AND MAXIMUM Y-VALUES": Ymin,Ymax

BEEP

INPUT "ENTER STEP SIZE FOR X-AXIS": Xstep

BEEP

INPUT "ENTER STEP SIZE FOR Y-AXIS": Ystep

END IF

BEEP

PRINT "IN:SP1:IP 2300,1800,8300,6800:"

PRINT "5C 0.100.0,100:TL 2.0:"

Sf*:100'():Xmax-Xmin)

Sfy:100'():Ymax-Ymin)

BEEP

Icg=0

INPUT "LIKE TO BY-PASS CAGE (1=I,0=N.DEFAULT)?", Icg

IF Icg=1 THEN 6175

IF Icg=0 THEN 6175

PRINT "PU 0.0 500"

FOR X=Xmin TO Xmax, STEP Xstep
X=(xa-xm1n)*SfX
PRINT "PA":",",0.XT;
NEXT Xa
PRINT "PA 100.0,0.0"
PRINT "PA 0,0 PD"
FOR xa=xmin TO xmax STEP Xstep
Y=(ya-ymin)*Sfy
PRINT "PA":",",100;XT"
NEXT Ya
PRINT "PA 100,0.0"
FOR xa=xmin TO xmax STEP Xstep
X=(xa-xm1n)*Sfx
PRINT "PA":",",0.0"
6135 PRINT "SR 1.5,2;PU PA 40,-10;LBq(1Mw/m;PR 0.5,1;SR 1,1.5;LBc:5"
6140 ELSE
6145 PRINT "DI PA 36,-10;LB(T;PR 0.5,-1;LBs,PR 0.5,1;LE-T,PR -2.4,3 PC PR"
6150 PRINT "LBoe,PR (5,1;LB)/X"
6155 END IF
6160 PRINT "DI 0,0 DI"
6165 Xig=1.E+6
6170 Xug=-1.E+6
6175 Xal=50
6180 Yal=55
6185 Nrun=0
6190 BEEP
6195 INPUT "WANT TO PLOT DATA FROM A FILE I-Y,O=N)7",Ok
6200 Xii=1.E+6
6205 Xule=-1.E+6
6210 Okp=0
6215 IF Ok=1 THEN
6220 BEEP
6225 INPUT "ENTER THE NAME OF THE PLOT DATA FILE",D_file$
6230 ASSIGN @File TO D_file$
6235 IF Icomb<>0 THEN 6265
6240 Sx=0
6245 Sy=0
6250 Sx2=0
6255 Sxy=0
6260 Md=1
6265 BEEP
6270 INPUT "ENTER THE BEGINNING RUN NUMBER (DEF=1)",Md
6275 Npairs=9
6280 BEEP
6285 INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED (DEF=9)",Npairs
6290 Nrun=Nrun+Npairs
6295 PRINTER IS 1
6300 BEEP
6305 PRINT USING "4X,""Select a symbol:"
6310 PRINT USING "4X,"" 1 Star 2 Plus sign"
6315 PRINT USING "4X,"" 3 Circle 4 Square"
6320 PRINT USING "4X,"" 5 Rombus"
6325 PRINT USING "4X,"" 6 Right-side-up triangle"
6330 PRINT USING "4X,"" 7 Up-side-down triangle"
6335 INPUT Sym
6340 BEEP
6345 INPUT "ENTER TUBE NUMBER FOR PLOTTING (0-TOP,1-SECOND....)";Itube
6350 PRINTER IS 70S
6355 IF Sym=1 THEN PRINT "SM+"
6360 IF Sym=2 THEN PRINT "SM-
6365 IF Sym=3 THEN PRINT "SMO"
6370 IF Md>1 THEN
6375 FOR I=1 TO (Md-1)
6380 ENTER @File:Xya(*)
6385 NEXT I
6390 END IF
6395 FOR I=1 TO Npairs
6400 ENTER @File:Xya(*)
6405 Y=Xya(Itube*2)
6410 X=Xya(Itube*2+1)
6415 Yc=LOG(Xa)
944e
644S
IF Itt-e THEN

E49O
Xt-Ya
G4SS
Ya-Y'e/X
6490£2= +>*
6E6-:
IF x/l.E4>~xil
THEN
Xul-Xa/.E+6

E461
~
IF X.e/1.E+6, K(2
THEN
xll=a/I.E+6

E47
9
9
END

E420 IF
Irt-0 THEN
6485 Xt=Xao1.E-E-Xmln)-St,
6492
Y
= Y
a
IE-

E6910 IF
I
Et=I
THEN
X)(X
-run
*Sf,

E6910
9675
END
:F Irt=Z

E S z y
Ya
I .E-3-Y m i
SfY

649S
END IF
6940 IF
Y>100 OR
YW0
THEN
6989
65S
IF
Symt
3
THEN
PRINT 'SM'
69C
IF Sym' THEN
PRINT SR
1.4,2.4
6999
PRINT
"A XY'
6.. IF
Sym 3
THEN PRINT
- SR
1.4,2.4
6ES IF Sym-4 THEN
PRINT "SM"
6999 IF Sym-7 THEN PRINT "R1216
UCB,-5.3,9B,-3,8,S,0,-3,8;'";
6929
NEXT I
6E90 BEEP
6955 INPUT "WANT TO LABEL (1-Y,0=N)9",1lbl
660E IF 1lbl=1 THEN
6600 IF Sym>3 THEN PRINT "SM"
6610 IF Sym<4 THEN PRINT "SR 1.4,2.4"
6615 PRINT "PA",Xal,Yal,"
6620 IF Sym>3 THEN PRINT "SR 1.2,1.6"
6625 IF Sym4 THEN PRINT "UC2,4.99,0,-8,-4,0,0,8,4,0:'
6630 IF Sym5 THEN PRINT "UC3,0.99,-3,-6,-3,6,3,6,2,-6:'
6635 IF Sym6 THEN PRINT "UC0,5,3,99,3,-8,-6,0,3,8:'
6640 IF Sym7 THEN PRINT "UC0,-S,3,99,-3,8,6,0,-3,-8:'
664S PRINT "SM"
6650 IF Sym4 THEN PRINT "PR 2,0"
6655 PRINT "PR 2,-1.0:SR 1.0,1.8;O_fileS:'"
6660 Yal=Yal-5
6665 BEEP
6675 IF Ias=1 THEN
6680 BEEP
6685 INPUT "ENTER THE STRING",Label$;
6690 PRINT "PR 2,0:SR 1.0,1.8;Label$:'"
6695 GOTO 6665
6700 END IF
6705 END IF
6710 BEEP
6715 INPUT "WANT TO COMBINE ANOTHER FILE? (1=Y,0=N)9",Icomb
ASSIGN @File TO *  
X11=5  
Xul=45  
IF Icom<>0 THEN 6220  
BEEP  
INPUT "WANT TO PLOT A LEAST-SQUARES LINE (1*Y,0=N)",I11s  
IF I11s=1 THEN  
BEEP  
INPUT "SELECT EXPONENT: 0=COMPUTE, 1=0.75",Iexp  
BEEP  
INPUT "SELECT CURVE TYPE (0=SOLID,1=DASHED)",Ilt  
Ilt=1lt+1  
PRINT "SM"  
IF Iexp=0 THEN  
Bb=(Nrun*Sxy-Sy*Sx)/(Nrun*Sx^2-Sx^2)  
ELSE  
Bb=.75  
END IF  
Aa=(Sy-Bb*Sx)/Nrun  
Aa=EXP(Aa)  
PRINTER IS !  
PRINT USING "10X,","a = "",2,4DE":Aa  
PRINT USING "10X,","n = "",2,4DE":Bb  
PRINTER IS 705  
In=0  
IF Int<>0 THEN Xxstep=Xstep*40  
IF Int>0 THEN Xxstep=Xstep/10  
FOR Xa=X11 TO Xul STEP Xxstep  
IF Xa>.99*Xmax THEN 6995  
IF Int=1 THEN Ya=Aa*Xa"Bb  
IF Int=0 THEN Ya=Aa"(1/Bb)*(Xa*1.E+5)/(Bb-1)/Bb  
IF Int=2 THEN Ya=Aa"(Bb-1)  
IF Int=0 THEN  
Y=(Ya=1.E-3-Ymin)*Sfy  
X=(Xa-Xmin)*Sfx  
END IF  
6830  
IF Int=1 THEN  
Y=(Ya=1.E-3-Ymin)*Sfy  
X=(Xa-Xmin)*Sfx  
END IF  
6850  
IF Int=2 THEN  
Y=(Ya=1.E-3-Ymin)*Sfy  
X=(Xa-Xmin)*Sfx  
END IF  
6860  
IF Y<0 THEN Y=0  
6870  
IF Y>100 THEN 6990  
6900  
IF Ilt=1 THEN  
PRINT "PA",X,Y,"PD"  
ELSE  
In=In+1  
Ir=In MOD 11t  
IF Ir=1 THEN PRINT "PA",X,Y,"PD"  
IF Ir=0 THEN PRINT "PA",X,Y,"PU"  
END IF  
6980  
NEXT Xa  
6995  
PRINT "PU"  }\n
END IR  
7005  
Icom=0  
7010  
GOTO 6185
END IF
7020 PRINT "PU 5M"
7025 BEEP
7030 INPUT "WANT TO PLOT NUSSELT LINE (1=ON, 0=OFF)?", inp
7035 IF inp=0 THEN 7125
7040 BEEP
7045 INPUT "ENTER TSAT (DEFAULT=18 DEG C)", Tsat
7050 Hfg=FNHf(Tsat)
7055 X1=5
7060 XU=45
7065 FOR Xa=X1 TO XU STEP Xstep/50
7070 Twl=Tsat-Xa*.5
7075 Kf=FNK(Tflml)
7080 Rhof=FRHof(Tflml)
7085 Huf=FMHuf(Tflml)
7090 ya=.728*(Kf^2-Rhof^2*9.81+Hfg)/(Huf+Do**x)*.25
7095 yx=(Xa-Xmin)*Sy
7100 PRINT "PA",X,Y,"PD"
7105 NEXT Xa
7110 PRINT "PU PA 0,0"
7120 PRINT "PU PA 0,0 SP0"
7125 SUBEND
7130 SUB Plot3
7135 COM /Dr1/ Star, Symbol, Icon
7140 COM /Dir/ Ift
7145 DIM C(9)
7150 Fu=1
7155 PRINTER IS 1
7160 BEEP
7165 PRINT USING "4X","Select Option X-Y Limits"
7170 PRINT USING "6X","0 Use default values"
7175 PRINT USING "6X","1 Use new values"
7180 INPUT O
7185 PRINTER IS 70S
7192 IF O=0 THEN
7195 Xmin=0
7200 Ymin=0
7210 Xmax=15
7215 Ymax=15
7220 Xstep=3
7225 Ystep=3
7235 ELSE
7240 BEEP
7245 INPUT "ENTER MINIMUM AND MAXIMUM X-VALUES", xmin, xmax
7250 BEEP
7255 INPUT "ENTER MINIMUM AND MAXIMUM Y-VALUES", ymin, ymax
7260 BEEP
7265 INPUT "ENTER STEP SIZE FOR X-AXIS", Xstep
7270 END IF
7275 BEEP
7280 PRINT "IN SP1:IP 2300,1800,8300,6800;"
7285 PRINT "SC 0,100,0,100,TL 2,0;"
7290 Sy=100/(Ymax-Ymin)
7295 Sx=100/(Xmax-Xmin)
7300 BEEP
7305 Icg=0
710 INPUT "LINE TO BY-PASS CAGE (1=YN, 0=N=DEFAULT)?", I
715 IF I<>1 THEN 7520
720 PRINT "PU 0.0 PC"
725 FOR I=1 TO 8 STEP 2
730 PRINT "PA 1,0,0.2"
735 NEXT I
740 PRINT "PA 1.0,0.2 PC"
745 FOR I=1 TO 8 STEP 2
750 PRINT "PA 1,0,0.2"
755 NEXT I
760 PRINT "PA 1.0,0.2 PC"
765 NEXT I
770 PRINT "PA 1.0,0.2 PC"
775 END
PRINT "PA -11,50 OF 2", LEN Y1, label$1.)a, "GI 0,1,1LB", y1abel$1, J
PRINT "OF 2,0 DIR"
Mrun=0
BEEP
INPUT "WANT TO PLOT DATA FROM A FILE (1xy,j=n)?", C
Xx=0
IF C=1 THEN
BEEP
INPUT "ENTER THE NAME OF THE PLOT DATA FILE", C_file$
ASSIGN @file TO 0_file$
IN = i_comb = 0 THEN "set
S=0
S+=2
S=2
Sx+=0
Sy+=0
M=1
BEEP
INPUT "ENTER THE BEGINNING RUN NUMBER DEF=1", M
Npairs=9
BEEP
INPUT "ENTER THE NUMBER OF PAIRS STORED (DEF=9), Npairs
BEEP
INPUT "SELECT TUBE NUMBER 0=CF,1=SEEING.....", Itube
Nnum=Nrun*Npairs
PRINTER IS 1
BEEP
PRINT USING "4X," "Select a symbol:", "'
PRINT USING "4X," "1 Star 2 Plus sign""
PRINT USING "4X," "3 Circle 4 Square""
PRINT USING "4X," "5 Rombus""
PRINT USING "4X," "6 Right-side-up triangle""
PRINT USING "4X," "7 Up-side-down triangle""
INPUT Sym
PRINTER IS 785
IF Sym=1 THEN PRINT "SM"
IF Sym=2 THEN PRINT "SM"
IF Sym=3 THEN PRINT "SMo"
IF Sym=4 THEN PRINT "U3",4,9,7,0,4,0,0;9,0,4,0;
IF Sym=5 THEN PRINT "UC3.0,99,-3,-E,-3,6,-6,-6,8.8,6,3,-6";
IF Sym=6 THEN PRINT "UC3,0,99,-3,-E,-3,6,3,6,3,-6";
END IF
END FOR
FOR I=1 TO Npairs
ENTER @file.xa,ya
Sx+=xa; Sy+=ya
Sx2=Sx+xa*2
Sy2=Sy+ya*2
X=(xa-xmin)*Sx/
Y=(ya-ymin)*Sy/
IF Y<100 OR Y<9 THEN 7810
IF Sym=3 THEN PRINT "SM"
IF Sym=4 THEN PRINT "SR 1,4,2,4";
PRINT "PA",X,Y,"",
IF Sym=3 THEN PRINT "SR 1,2,1,6"
IF Sym=4 THEN PRINT "UC2,4,99,0,-6,-4,0,0,8,4,0;9,0,4,0;
IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6";
IF Sym=6 THEN PRINT "UC0,5,3,99,3,-6,-6,0,3,8."
IF Sym=7 THEN PRINT "UC0,-5.3,99.3,6.6,0,-3.5."
NEXT I
BEEP
INPUT "WANT TO LABEL (1=Y,0=N)?",Ibl
IF Ibl=1 THEN
IF Sym=3 THEN PRINT "SM"
IF Sym=4 THEN PRINT "SR 1.4,2.4"
PRINT "PA",Xa,Ya,"PD"
IF Sym=3 THEN PRINT "SR 1.2,1.6"
IF Sym=4 THEN PRINT "UC2,4,99.0,-8.4,0,8.4,0;"
IF Sym=5 THEN PRINT "UC3,0.99,-3.6,-7.6,3.6,3.6,6.6;"
IF Sym=6 THEN PRINT "UC0,5.3,99.3,-8.6,0,3.8;"
IF Sym=7 THEN PRINT "UC0,-5.3,99.3,6.6,0,-2.8;"
PRINT "SM"
IF Sym=4 THEN PRINT "PR 2,0"
PRINT "PR 2,-1.0,SR 1.0,1.8:LB","D_file";
Ya=Ya-5
INPUT "WANT TO ADD ANOTHER STRING (1=Y,0=N)?",Ies
IF Ies=1 THEN
BEEP
INPUT "ENTER THE STRING",Label$,
PRINT "PR 2,0,SR 1.0,1.8:LB","Label$;"
GOTO 7900
END IF
END IF
BEEP
INPUT "WANT TO COMBINE ANOTHER FILE? (1=Y,0=N),Icomb
ASSIGN @Pile TO *
IF Icomb=0 THEN 7645
Ils=1
BEEP
INPUT "WANT TO PLOT A LEAST-SQUARES LINE (1=DEF=YES,0=NO)?",Ils
IF Ils=1 THEN
BEEP
INPUT "SELECT CURVE TYPE (0=SMOOTH,1=DASHED)?",Ilit
Ilit=Ilit+1
PRINT "SM"
IF Ilit=0 THEN
Bb=1/Run*(Sy-Sx)*Run*Sx+Sy*Sy
ELSE
END IF
Aa=(Sy-Bc*Sx)/Run
PRINTER IS 1
PRINT USING "\10X","a=","M2.3DE",Aa
PRINT USING "\10X","n=","M2.3DE",Bb
PRINTER IS 705
In=0
FOR X=xmin TO xmax STEP (xmax-xmin)
Y=a*X+b
Y=(Ya-Ymin)*Sfy
Y=Ym+Ymin*Sfy
IF Y<0 THEN Y=0
IF Y>100 THEN GOTO 8220
IF Ilit=1 THEN
PRINT "PA",X,Y,"PD"
ELSE
In=In+1
Ir=In MOD Ilit
IF Ir=1 THEN PRINT "PA",X,Y,"PD"
IF I=0 THEN PRINT "PA",X,Y,"PU"

END IF

NEXT Xa

PRINT "PU"

END IF

Icomb=0

GOTO 7620

END IF

PRINT "PU PA 0,0"

PRINT "PU PA 0,0 SP0"

SUBEND
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