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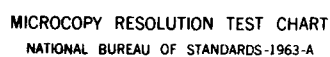
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NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

FILMWISE CONDENSATION OF STEAM ON
EXTERNALLY-FINNED HORIZONTAL TUBES

by

William M. Poole

December 1983

Thesis Advisor:

P. J. Marto

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Condensation data taken for the smooth tube were compared with data in the literature to check the reliability of the apparatus and the data-reduction procedures. The data for the finned tubes showed an optimum pitch of 2.5 mm.

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**Filmwise Condensation of Steam on
Externally-finned Horizontal Tubes**

by

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Lieutenant, United States Navy
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U.S. Naval Academy, 1978

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The film-condensation characteristics of a smooth tube and six externally-finned tubes having fins 1 mm high and 1 mm thick, and pitches of 1.5, 2.0, 2.5, 3.0, 5.0, and 10.0 mm, were experimentally tested.

A smooth copper tube with an active length of 133.5 mm, an outside diameter of 19.05 mm, and an inside diameter of 12.7 mm was first tested to correlate the inside heat-transfer coefficient using the Sieder-Tate equation. The leading coefficient for this equation was found to be 0.034 + or - $\pm$ 0.001, and was used to derive the external condensing coefficient for all of the tubes by subtracting the inside and wall resistances from the measured overall resistance. The condensing coefficient was measured, both at atmospheric pressure and vacuum (84 mm Hg), with the heat flux as a variable.

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NOMENCLATURE

c_p	Specific heat, kJ/kg-K
D_i	Inner diameter, m
D_o	Outer diameter, m
F	Parameter, $gd\mu h_g/u^2 k \Delta T$
g	Acceleration due to gravity, m/s ²
Gr_A	Grashof number of air, $g(\beta(T_w - T_\infty) L^3/\nu^2$
h	Heat-transfer coefficient, W/m ² -K
h_g	Latent heat of vaporization, kJ/kg
k	Thermal conductivity, W/m-K
k_A	Thermal conductivity of air, W/m-K
k_g	Thermal conductivity of glass, W/m-K
k_L	Thermal conductivity of liquid, W/m-K
L	Length, m
L_b	Length of the boiler, m
Nu	Nusselt number, hd_o/k
p	Pressure, MPa
Pr	Prandtl number, $\mu c_p/k$
Q	Heat transfer rate, W
q	Heat flux, W/m ²
R	Thermal resistance, K/W
R_w	Wall thermal resistance $(D_o \ln(D_o/D_i)/2k_w)$, K/W

$r_{i,b}$	Inner radius of the boiler, m
$r_{o,b}$	Outer radius of the boiler, m
Ra	Rayleigh number, GrPr
Re	Reynolds number, $u_{\infty} D_o / \nu_{\infty}$
$\tilde{Re}$	Two-phase Reynolds number, $u_{\infty} D_o / \nu_L$
T	Temperature, °C
T_f	Film temperature, °C
$T_{i,b}$	Inner wall temperature of the boiler, °C
$T_{o,b}$	Outer wall temperature of the boiler, °C
T_{∞}	Ambient temperature, °C
$\bar{T}$	Average temperature, °C
u	Velocity, m/s
u_{∞}	Vapor velocity, m/s
U_o	Overall heat-transfer coefficient, W/m ² -K
X	Parameter, $D \nu^{1/3} / Z k_L$
Y	Parameter, $\nu^{1/3} [1/U_o - R_w]$
Z	Sieder-Tate parameter, $Re^{0.8} Pr^{1/3} (\mu/\mu_w)^{0.14}$
β	Expansion coefficient of air, K ⁻¹
μ	Dynamic viscosity, N-s/m ²
ν	Kinematic viscosity, m ² /s

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I. INTRODUCTION

A. BACKGROUND

As combat systems aboard naval surface ships continue to grow in importance, size, and weight, the feasibility of their installation aboard lightweight vessels can only be realized by reducing other major shipboard weight requirements. A significant achievement in reducing main propulsion weight was reached with the advent of gas-turbine propulsion plants, of which the majority of our new combatants will be powered. However, for the remaining capital ships and submarines to be constructed using either conventional or nuclear steam systems, power plant weight reduction can only be realized by increasing the effectiveness of the individual plant components and thereby reducing their size. Plans call for future installation of Rankine-cycle waste-heat recovery systems even on those ships with gas-turbine propulsion, so significant weight reduction could also be realized there through the use of more effective systems.

Due to the nature of the condensing process, the greatest thermal resistance to condenser-tube heat transfer occurs on the tube side, and a thorough review of tube-side enhancement is presented by Bergles and Jensen [Ref. 1]. Internal enhancement of the tube without regard to the shell-side resistance problem, however, would be a wasted effort if improvements were made to the point where the external (shell-side) resistance became the controlling factor in the transfer of heat. Recent investigations into the shell-side condensing process and techniques to improve this process are thoroughly reviewed by Marto [Ref. 2]. Outside enhancement techniques include the use of low

integral fins, roped tubes, fluted tubes, and applied coatings to promote dropwise condensation.

Ongoing research is underway at the Naval Postgraduate School to further study the shell-side enhancement of marine condensers. An endurance apparatus is in operation to examine the dropwise-promoting effectiveness of various metallic and polymer coatings over prolonged periods of time. Reilly [Ref. 3] conducted a study of improvements using various spirally fluted tubes under filmwise condensation, and the effects of tube bundle inundation have also been studied by Kanakis [Ref. 4].

A test apparatus has been constructed by Krohn [Ref. 5] to systematically study steam condensation on a single horizontal tube. The apparatus is modeled after a similar design constructed by Rose [Ref. 6], but can also operate under the high-vacuum conditions found in marine condensers and without the presence of noncondensable gases. This test apparatus was instrumented and tested by Graber [Ref. 7], who determined the Sieder-Tate coefficient for the test tube length to be 0.029.

In experiments using low integral fins at Queen Mary College of London, Rose, et. al., [Ref. 6] obtained an optimum pitch of 2.0 mm (0.08 in.) for a given fin size of 1 mm (0.04 in) high and 0.5 mm (0.02 in) wide for tests conducted at one atmosphere. With this pitch, he reported vapor-side heat-transfer enhancements of 400% and 300% for heat fluxes of 0.3 MW/m² (9.51×10^4 Btu/hr-ft²) and 0.8 MW/m² (2.54×10^5 Btu/hr-ft²), respectively, and for a vapor velocity of 0.7 m/s (2.3 ft/sec). Further testing is needed to compare these results with similar fin geometries under vacuum conditions, while varying fin dimensions (height and width) in addition to the fin pitch.

B. OBJECTIVE

The main objectives of this research effort were, therefore, to:

- 1) ensure a vacuum-tight apparatus so that data could be taken at both atmospheric and vacuum conditions with no detrimental effects due to the presence of noncondensable gases;
- 2) take data for an instrumented smooth tube to verify the Sieder-Rate coefficient obtained by Graber;
- 3) take data for a smooth tube to check the reliability of the apparatus and the data-reduction procedures used; and
- 4) take data for six externally-enhanced tubes of various fin pitches to obtain the relative optimum pitch for a fixed fin geometry.

II. DESCRIPTION OF APPARATUS

A. SYSTEM OVERVIEW

The apparatus used for this research was essentially the same used in references 5 and 7, with several noted modifications. A schematic sketch of the system is shown in Figure 2.1. Steam was generated in a 304.8-mm (12-in) diameter Pyrex glass boiler by ten 4000-watt, 480-volt Watlow immersion heaters. Passing through a 304.8-mm (12-in) to 152.4-mm (6-in) reducing section, the steam travelled upward through a Pyrex section 2.44 m (8.0 ft) in length, around a 180-degree bend, and back down a straightening section 1.52 m (5.0 ft) in length before entering the stainless-steel test section. The condenser tube to be tested was mounted horizontally in the test section behind a viewport to permit visual observation of the condensing process.

Steam that did not condense on the test tube passed into a stainless steel auxiliary condenser, and all condensate was returned via gravity to the boiler. The auxiliary condenser was constructed of two 9.5-mm (3/8-in) water-cooled copper lines helically coiled to a height of 457 mm (18 in).

Cooling water for the test tube was provided by two centrifugal pumps connected in series. The water could be throttled from zero flow to 0.69 l/s (11 gpm). The maximum water velocity which could be obtained through the tube was 5.48 m/s (18 ft/sec). A continuous supply of tap water was used for cooling the auxiliary condenser. Throttling the flow of tap water through the condenser was the means used to vary the internal pressure of the test apparatus. The water flow through both the test tube and the auxiliary

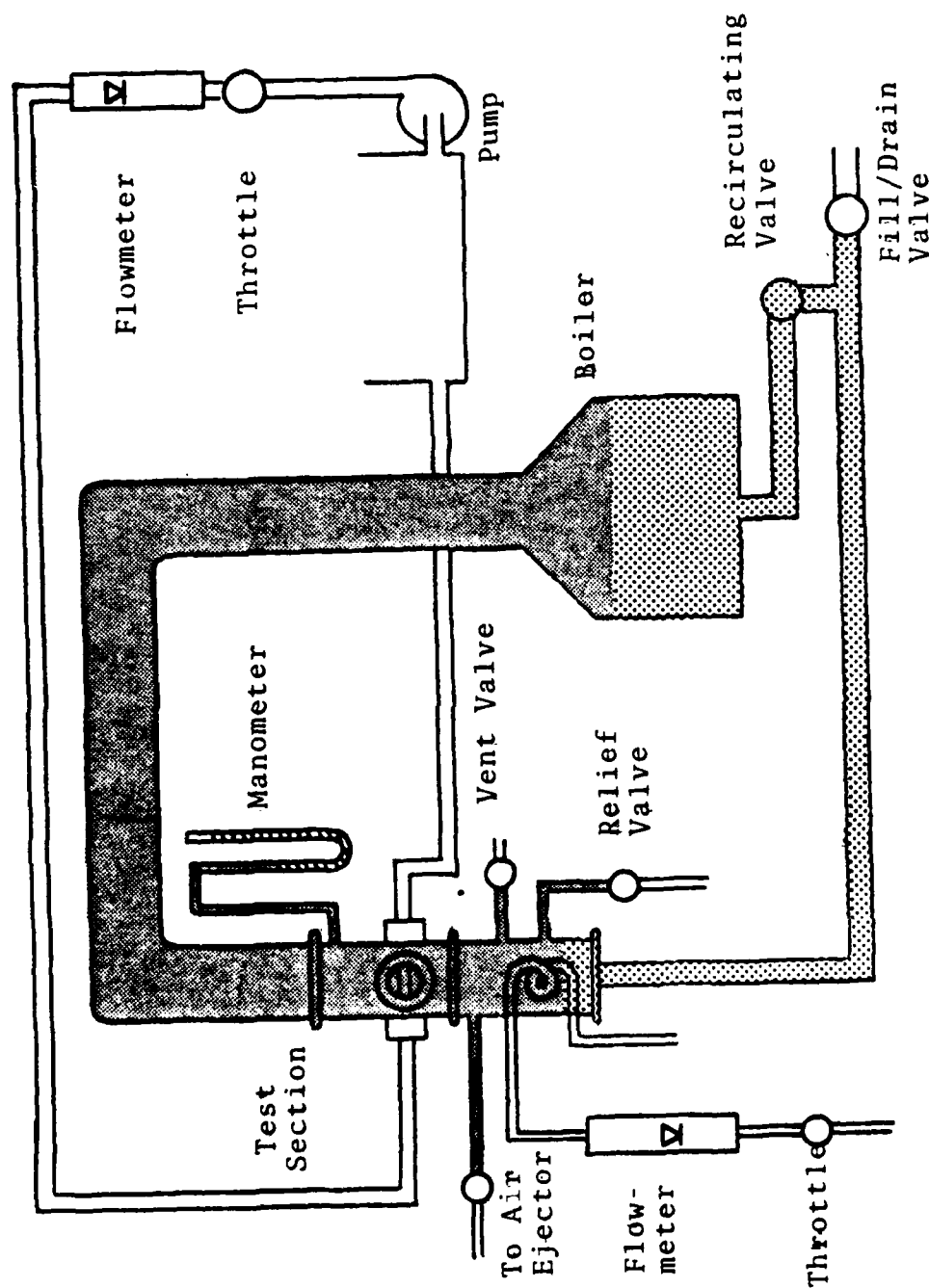


Figure 2.1 Schematic of the test apparatus.

condenser was regulated by 19.1 mm (3/4 in) diameter needle valves and measured by rotameters with full-scale ranges of 0.69 l/s (11 gpm).

An air ejector provided for removal of noncondensable gases from the auxiliary condenser through a 12.7-mm (1/2-in) line. The source for the air ejector was 1.1-MPa (160-psig) house-air supply.

B. SYSTEM INSTRUMENTATION

The input voltage through the heaters was varied through a panel-mounted potentiometer. 440-VAC line voltage was reduced by a factor of 100 when fed into a differential input precession voltage attenuator. The stepped-down voltage passed through a True-RMS converter stage on which the integrated period was reduced to about 1 ms. The output of the TRMS converter was then buffed and compared to a reference voltage from the potentiometer. The comparator output was fed to the control input of a Halmar silicon-controlled rectifier power supply which applied the actual voltage to the heaters. The TRMS converter output was also paralleled to a filter and then input to the data acquisition system. This input was proportional to the power supply output. A diagram of the system is shown in Figure 2.2.

The internal pressure of the system was measured manually by a U-tube, mercury-in-glass manometer graduated in millimeters. Unavoidably, steam could condense in the manometer. Therefore, the varying height of the water column in the manometer needed to be accounted for when measuring the system pressure.

Temperatures throughout the system were measured by copper-constantan thermocouples: six for the wall of a specially-constructed test tube, two for the steam, and one

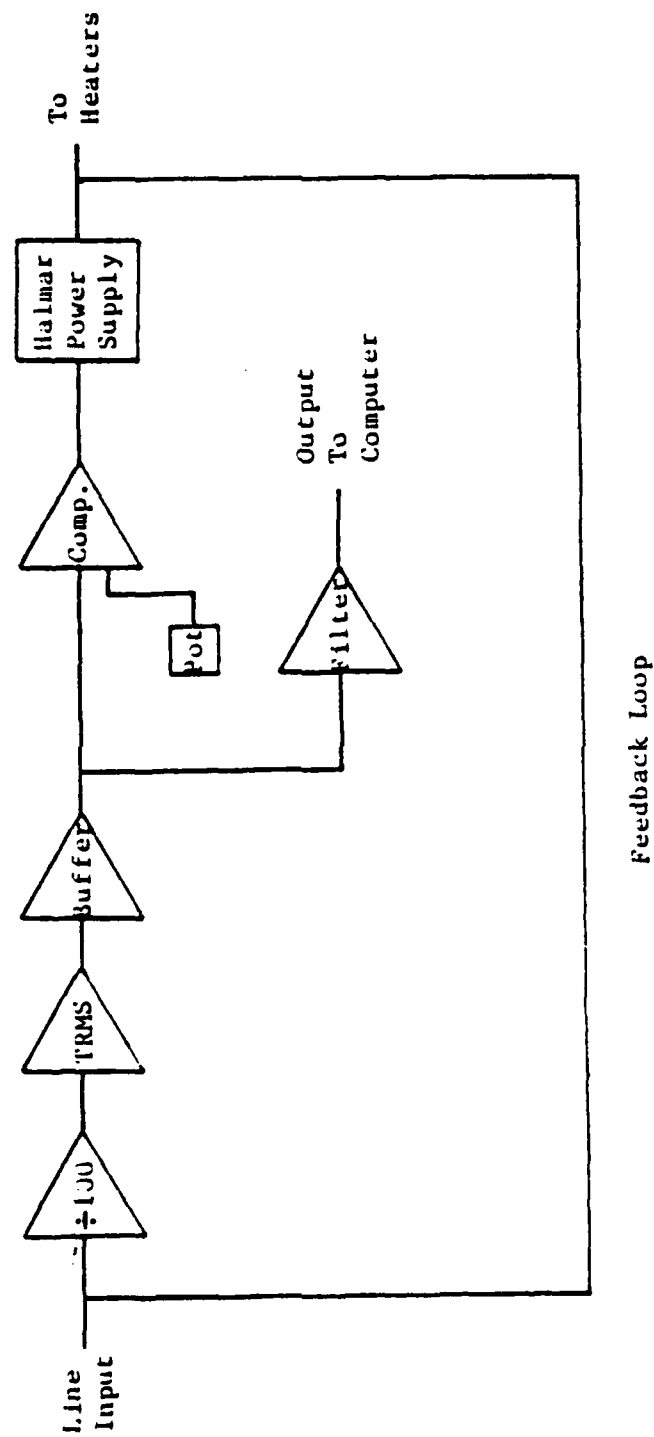


Figure 2.2 Line diagram of the power supply.

each for the cooling-water inlet, condensate return, and ambient. The calibration procedure for these thermocouples is described in Appendix A. The temperature rise through the test tube was measured by a Hewlett-Packard (HP) 2804A quartz thermometer.

All temperature measurements were fed directly into the data-acquisition system as described below.

C. DATA ACQUISITION

An HP 3497A Data Acquisition/Control Unit was used to monitor system temperatures. This was interfaced with an HP 9826A computer which served as a controlling unit through an interactive data-reduction program and user keyboard prompts. Raw data gathered by the data-acquisition system were stored on computer disks for later reduction and evaluation.

D. SYSTEM MODIFICATIONS

1. Boiler

The fiberglass insulation was removed from the boiler to allow the operator to more easily monitor the water level. Although a closed-system design was used, it was still possible for steam to escape via the air ejector or through the relief valve [Fig. 2.1]. Calculations showed that the additional heat loss due to the removal of the insulation was minimal [App. B], and the author felt this loss was much more acceptable than risking damage to the immersion heaters through a low-water casualty in the boiler.

2. Condensate Piping

As originally designed, draining the system required breaking down the condensate piping. While this was not a daily occurrence, the procedure was inconvenient and there existed also the possibility of losing the vacuum integrity of the system each time it was done.

To avoid these problems, the existing fill-line valves were rearranged as shown in Figure 2.1. This arrangement also added two additional features to the system:

- 1) the fill/drain valve could be opened during operation to drain any heavy particulate matter from the system - similar to the "bottom blow" procedure used on Naval boilers; and
- 2) after extended periods of inactivity while opened to the atmosphere, the entire system could be given a thorough steam-cleaning by following the procedures outlined in Appendix C.

3. Vent Valve

The modification of the condensate return piping necessitated the addition of a vent valve for use when filling or draining the system. A 4.3-mm (0.17-in) needle valve was installed on the 101.6-mm (4-in) flange of the test section. This valve would also serve as the tap for the proposed sampling of noncondensable gas concentrations in the system.

4. Manometer Line

The original system design used a 6.4-mm (1/4-in) stainless steel tube angled down to the mercury manometer. During this thesis, the manometer was raised to eye level to facilitate easier and quicker reading. Replacement of the

stainless-steel line by a 12.7-mm (1/2-in) copper tube reduced the possibility of error caused by water slugs building up in the smaller diameter tube. The more workable copper was chosen over stainless steel to reduce the stiffness of the connecting line. This was necessary to eliminate leakage in this part of the apparatus as explained in Section II.E.

5. Pressure Transducer

As an alternative to the manometer, a Celesco strain-gage pressure transducer was installed on the test section flange next to the vent valve. The calibration line for the transducer is shown in Figure 2.3. The author felt, however, that the reliability of this measurement would not be high enough until a second, more accurate transducer was installed. Once incorporated into the system, though, these transducers would provide automatic input to the data acquisition system, eliminating the requirement to manually enter the manometer reading into the data-reduction program.

6. Relief Valve

As originally designed, a 6895-Pa gage pressure (1.0-psig) relief valve was installed beneath a 1.0-m (39.4-in) length of 12.7-mm (1/2-in) stainless-steel piping. Steam which condensed and became trapped in this piping would open the valve at a water-column height of only 0.70 m (27.6 in). Once opened, a back-pressure of 0.14 MPa gage (20 psig) was required to reseal the valve - something unobtainable even with an absolute vacuum on the inlet side of the valve. To avoid this problem, the valve was raised in the line to a point only 76 mm (3.0 in) below the outlet from the auxiliary condenser section and was replaced by another 6895 Pa gage pressure (1.0-psig) relief valve which reseated at only 0.04-MPa gage (6-psig) back-pressure.

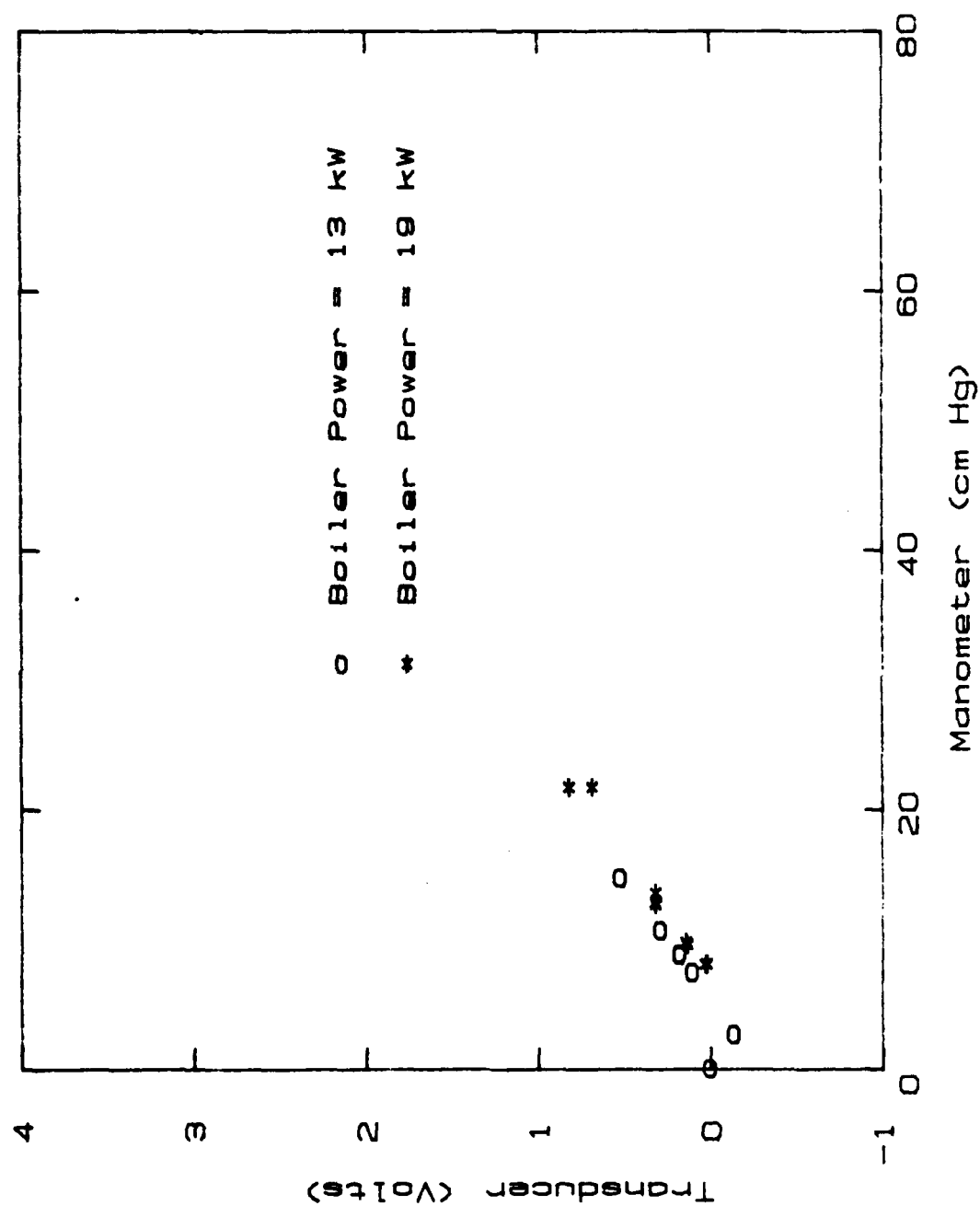


Figure 2.3 Calibration of the pressure transducer.

7. Steam-temperature Probe

The steam temperature probe was located directly above the test tube and shared the same inlet to the test section as the manometer line. When drawing a high vacuum, this arrangement allowed water which had collected in the manometer to be drawn back into the test section where it would flow down the probe and onto the tube. To prevent this water and any contaminants picked up in the manometer from being deposited on the tube, the probe was bent so that it was offset from the center of the test tube.

8. Cooling Water System

A second centrifugal pump was added in series to the one already installed. This pump boosted the maximum cooling water velocity through the test tube from 3.96 m/s (13 ft/sec) to 5.48 m/s (18 ft/sec).

The 10.55 kW (3 Ton) air-conditioning unit used with the cooling water system would energize at a water temperature of 17 °C (62.6 °F) and secure when the temperature was reduced to 13.4 °C (56.1 °F). Therefore, for a given steam temperature of 50 °C (122 °F) around the tube, the log-mean-temperature difference would vary by as much as 11%. But the measured temperature rise of the water through the tube showed very little change. To avoid this transient problem, the air-conditioning unit was not used, and instead fresh tap water was continuously fed to the sump while an equal amount of water was being drained, maintaining a constant sump level. This method provided a constant-temperature supply of cooling water to the inlet side of the test tube.

It should be pointed out that, while the duty cycle of the air-conditioning unit was a function of the thermostat used, a more sensitive thermostat would require the

use of a more expensive cooling device than a commercial air conditioner. An alternative solution would be to install a much larger sump in the system.

9. Thermopile

Since the temperature rise of the cooling water through the tube was a critical measurement in the experiment, a 10-junction thermopile was added to measure this temperature rise in addition to the quartz thermometer. As will be explained in Section V.A.3, however, problems arose with the thermopile, and it could not be accurately used during this thesis.

B. VACUUM INTEGRITY

One of the objectives of this thesis was to ensure a vacuum-tight test apparatus to eliminate the presence of any noncondensable gases and their detrimental effects on the condensing process. A standard of no more than a 5.0-mm mercury (0.10-psi) loss over a 24-hr period was considered to be an acceptable tolerance, but obtaining a leak rate within this tolerance proved to be the most time-consuming effort during the research.

Due to the construction of the apparatus and nature of the experiment, most leak-detection methods could not be used. A sealing substance could not be used without risking contamination of the interior of the apparatus which might prohibit filmwise condensation on the test tube.

Initially the system was pressurized and the standard soap-solution test was used to locate leaks. Once pressurized, a liquid-soap solution was applied to each external joint or fitting where a leak could be present. The higher pressure air inside the apparatus would escape through any leaks and produce bubbles on the applied soap film.

However, the maximum pressure which the Pyrex glass members could tolerate was only 0.074 MPa gage (10.7 psig), and for safety reasons the author chose not to pressurize the system to more than 0.034 MPa gage (5.0 psig) - a pressure difference between the atmosphere and the apparatus of only 0.040 MPa (5.8 psi). The numerous external valves and fittings prohibited the use of an evacuated hood to achieve a greater pressure difference.

A similar test could not be used to locate any vacuum leaks which were not present when the system was under a positive pressure, as the apparatus was not large enough to permit the application and observation of a soap solution on the interior.

In another attempt to locate the leaks, a National Research Corporation (NRC) 101.6-mm (4-in) vacuum pumping system was connected to the apparatus. This pumping system included a Welch model 1376M mechanical pump and a model NHS-4 diffusion pump. An NRC model 521 thermocouple gage was also connected to the test apparatus and the entire apparatus was evacuated to 0.21 torr (4.1×10^{-3} psia). Acetone was sprayed around all flanges, fittings, and joints. A leak around any of these should have produced a rapid rise in the thermocouple reading, but this method also proved ineffective, probably due to the large size of the apparatus resulting in too great a mean free path for the acetone molecules to travel from the leak to the thermocouple.

The next alternative was to break the system apart into three main sections: the glass boiler and steam piping, the stainless-steel test section and auxiliary condenser, and the condensate return piping. The glass section was blank-flanged and evacuated to an absolute pressure of 0.033 torr (6.4×10^{-4} psia). The rate-of-rise measurement for this section showed a loss of only 0.48 mm of mercury (0.01 psi) over a 30-hr period. It was, therefore, concluded that any leak in the assembled apparatus was not from this section.

Once removed, the test section and the auxiliary condenser were blank-flanged, pressurized to 0.10 MPa gage (15 psig), and immersed in a large plexiglas tank filled with water. This test easily revealed a number of small leaks about the inlet side of the test tube and also around the plug which connected the condensate return piping to the base of the auxiliary condenser. Replacing an O-ring in the tube fitting and silver brazing the plug into place eliminated these leaks.

The same immersion test revealed small leaks in the joints of the condensate return piping. These leaks were eliminated by replacing all stainless-steel ferrules in the Swagelok fittings with teflon ferrules.

Once reassembled, considerable leakage was still indicated by a substantial overnight rise in the manometer level. The author felt confident that this leak was not in the main assembly of the apparatus, but was instead in the manometer assembly itself since it could not be pressurized for testing. As mentioned in section II.C.4, the stainless-steel line leading to the manometer was at this time replaced by a 12.7-mm (1/2-in) soft copper tube. This tube eliminated the need for two 90-degree elbows and three lengths of stainless steel tubing in the line - an assembly which proved too rigid to allow even the slightest misalignment into the manometer.

Upon completion of the installation of this assembly, the system was evacuated to an absolute pressure of 92.5 mm Hg and over a 24-hr period the mercury level rose to only 94.0 mm. This leak rate was well within the acceptable tolerance.

F. TUBES TESTED

1. Instrumented Tube

An instrumented tube was fabricated from a thick-walled copper tube with an inner diameter of 12.70 mm (1/2 in) and an outer diameter of 19.05 mm (3/4 in). The tube was cut into three sections into which six holes were drilled axially along the walls at equal spacings 60 apart. These passages were fitted with 0.094-mm (3/32-in) OD capillaries [Fig. 2.4] which were silver-soldered into place, and the three sections of tube were then soldered back into one piece. Thermocouples were fitted into the capillary sections to measure an average wall temperature.

By knowing the average wall temperature, the Nusselt number for the inside could be computed. By computing the gradient of the Nusselt number against the Sieder-Tate parameter, the inside coefficient could be obtained as the inverse of the gradient. Figure 2.5 shows a photograph of the instrumented tube with the installed thermocouples.

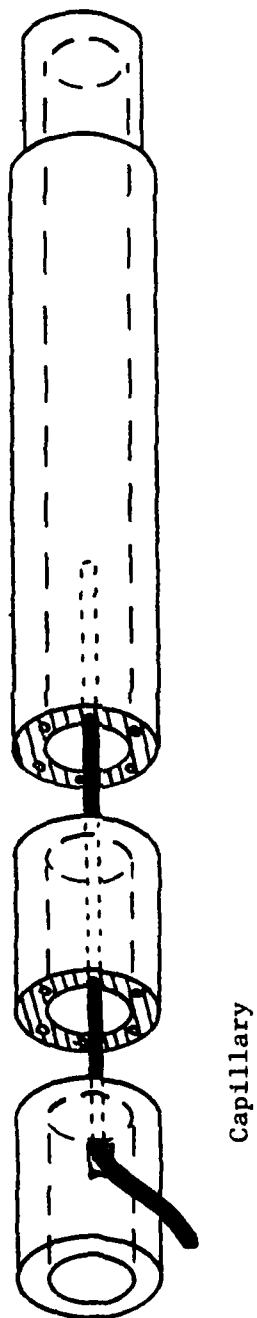


Figure 2.4 Schematic of the instrumented tube construction.

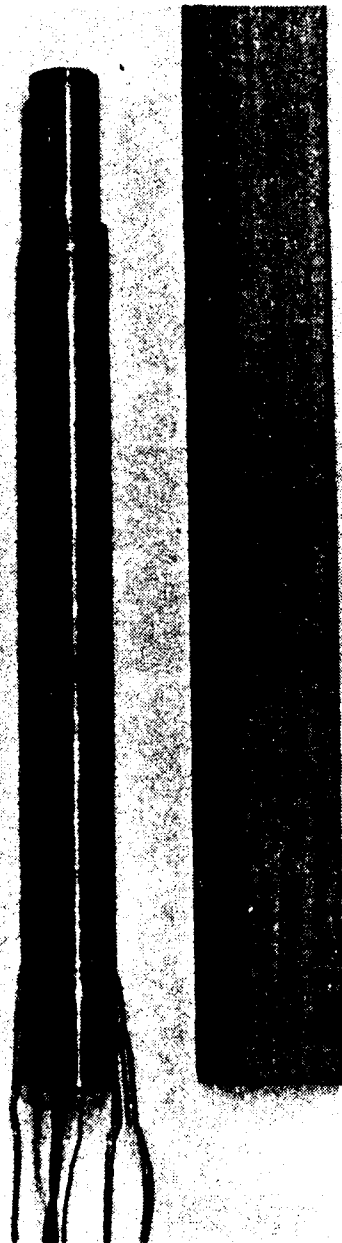


Figure 2.5 Photograph of the instrumented tube.

2. Smooth Tube

A smooth tube with no wall thermocouples was also tested to obtain the inside heat-transfer coefficient through the use of a modified Wilson Plot [Ref. 8]. Determination of the inside heat-transfer coefficient was critical to the experiment, as it was used to obtain the outside condensing coefficient for the smooth tube and all of the enhanced tubes.

3. Finned Tubes

To fulfill the main objective of this thesis, a series of six finned tubes was also tested [Fig. 2.6]. These tubes had the same overall dimensions as those above, but were enhanced with radial fins 1 mm (0.04 in) high and 1 mm (0.04 in) thick. Each tube had a different fin pitch and was tested to determine a relative optimum pitch. Fin pitches tested were 1.5, 2.0, 2.5, 3.0, 5.0, and 10.0 mm.

G. SYSTEM OPERATION

The tube to be tested was cleaned in a warm solution of Sparkleen and then rinsed with tap water, which produced a contaminant-free, wetted surface. The tube was then installed in the test section, care being taken not to touch or contaminate the condensing surface.

The system was brought to operating pressure by following the procedures of Appendix D, and data collection began when steady-state conditions were achieved. Steady-state conditions were determined by observing the steam temperature measured by the respective thermocouples. When their output voltage on the HP 3497A reached a constant value with fluctuations of only one or two microvolts, it was assumed that steady-state conditions existed in the test apparatus.



Figure 2.6 Photograph of the finned tubes tested.

Data sets were taken starting with a test-tube cooling water flow rate of 90% (which corresponded to a water velocity of 4.95 m/s or 16.2 ft/sec), ranging downward in decrements of 10% through a minimum flow of 20% (1.16 m/s, 3.8 ft/sec), and then upward from 25% to 85% in increments of 10%. After adjusting the flow rate, the temperature rise through the tube was monitored by observing the digital output of the quartz thermometer. When this rise became constant, another set of data could be taken. During data runs, a slight rise in pressure accompanied the decrease in the cooling water flow through the tube, a result of the reduced heat flux. Similarly, increasing the flow through the tube caused a slight decrease in the system pressure. This variance could be anticipated, and since data were to be collected at a constant pressure, it was easily compensated for by throttling the flow of cooling water through the auxiliary condenser one or two percentage points on the rotameter.

Something which could not be anticipated, however, were sudden fluctuations in the tapwater pressure to the auxiliary condenser which caused pressure changes of several millimeters of mercury in the system. To avoid this problem, the flow through the auxiliary condenser had to be continuously monitored, unless data were being taken late at night when there was no demand on the laboratory building's water supply. The test tube could be easily monitored through the viewport for confirmation of filmwise conditions. If there was any sizeable change to dropwise condensation on the tube, the data set was discarded and the procedure was repeated.

III. FILMWISE CONDENSATION

A. THE DROPWISE PROBLEM

It was essential during the course of this thesis to collect data under filmwise conditions. Numerous problems were encountered by Graber [Ref. 7] in avoiding the transition to dropwise condensation during operation, and his proposed solution was a vacuum-tight test apparatus. Since the tube surface would wet completely after installation, contaminants leaking into the system were possibly adhering to the surface and promoting the dropwise condensation.

However, even after obtaining a vacuum-tight apparatus, the author was still unable to maintain good filmwise condensation for more than two hours on a smooth tube. While this was enough time to collect a complete set of data for this tube, filmwise condensation lasted seventeen minutes at the most on any of the finned tubes, the average time being less than ten minutes. This was predictable - the corners of the fin/surface interfaces provided a better trap for contaminants and were harder to clean - but unacceptable.

The use of the steam-cleaning method described in Appendix C would thoroughly clean the tube so that complete filmwise condensation was re-established, but dropwise condensation would again become prevalent within minutes.

B. SOLUTION

Having eliminated the possibilities of installing a dirty tube or contamination due to leakage, the only reason for the dropwise problem had to be coming from outgassing of the nylon holders for the test tube. The outgassing rate for nylon was found to be almost two orders of magnitude greater

than the rate for Teflon [Ref. 9], Teflon being the same order as stainless steel. By pumping down the apparatus while it was hot, nylon molecules were being outgassed into the test section and were immediately being deposited onto the surface of the cooler test tube, resulting in inadvertant "sputtering" of the tube with a nylon coating and subsequent dropwise condensation. To eliminate the nylon interface with the interior of the test section, special stainless steel caps were manufactured to slip over the nylon holders.

Teflon bushings were fitted within the caps to insulate them from the tube. Teflon had both a low thermal conductivity and a relatively low outgassing rate. Figure 3.1 shows a detailed sketch of the installation.

This configuration appeared to solve the problem of dropwise condensation. Although an actual endurance test was not conducted, the system was in operation intermittantly for over fifteen hours with the smooth tube and over four hours with each finned tube with no breakup of the filmwise condensation.

Once installed, this arrangement also eliminated the need for the tube-cleaning procedure recommended by Graber [Ref. 7], who felt that a strong cleaning solution of sodium hydroxide and ethanol was needed to decontaminate the surface. Only a warm solution of Sparkleen was used throughout the data-collection stage of this thesis.

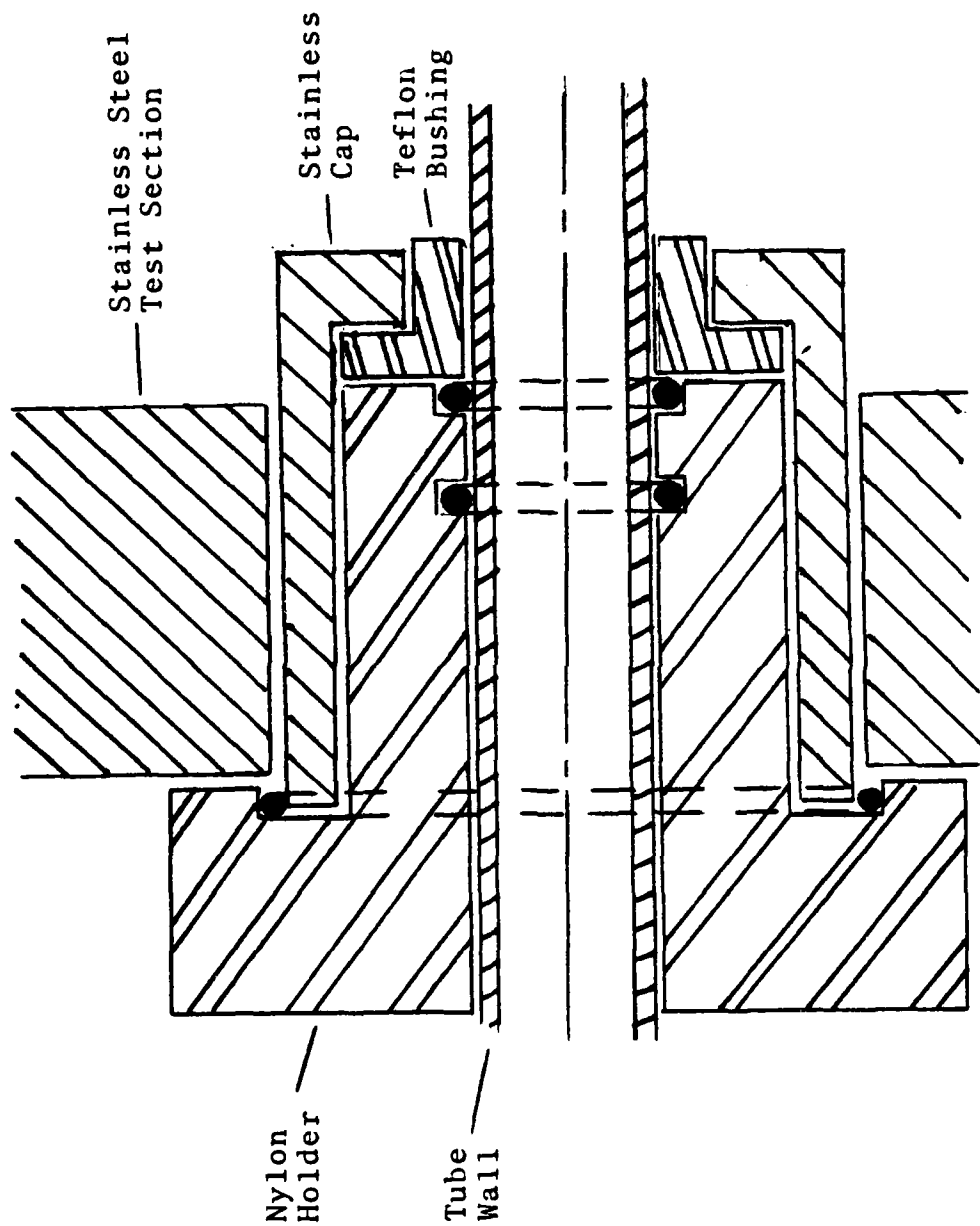


Figure 3.1 Cross-sectional view of the tube and holders.

C. VAPOR VELOCITY LIMITATIONS

To check the outside heat-transfer coefficient data with the Nusselt prediction, and also to obtain an accurate inside coefficient with the modified Wilson Plot, vapor velocities approaching zero were preferred. Due to the design of the system, however, the pressure drop to the auxiliary condenser required vapor flow past the test tube. This being the case, attempts were made to minimize this flow velocity by cutting down the power to the boiler and throttling back on the cooling water supply to the condenser. As vapor velocity was decreased, however, dropwise condensation again took place on the test tube. Under atmospheric pressure, this occurrence was at vapor velocities of about 0.5 m/s (1.6 ft/sec), and under vacuum operations it occurred at about 0.9 m/s (3.0 ft/sec). Apparently there still existed a sizeable rate of outgassing within the test section, those gases collecting about the test tube and interfering with the filmwise condensation process. This suspicion was confirmed when an increase in the vapor velocity eliminated the formation of drops on the tube.

IV. DATA REDUCTION

The data collected and stored on the computer disks reduced using the programs WILSON, SIEDER, and DRP. The programs were amenable to changes, which allowed the author to analyze and compare results while varying parameters within the programs. Stepwise reduction procedures for each program are listed below and the program listings are found in Appendix E.

A. PROGRAM SIEDER

1. Compute the average cooling water temperature.
2. Compute the average wall temperature.
3. Compute the cooling water velocity.
4. Compute the mass-flow rate of the cooling water.
5. Compute the heat transferred to the cooling water.
6. Compute the average inside wall temperature.
7. Compute the log-mean-temperature difference.
8. Compute the inside heat-transfer coefficient.
9. Compute the Nusselt number.
10. Compute the Sieder-Tate parameter.
11. Compute the inside coefficient.

B. PROGRAM WILSON

1. Assume a value for the Sieder-Tate coefficient.
2. Compute the Reynolds and Prandtl numbers for flow through the tube.
3. Compute the log-mean-temperature difference, heat flux, and overall heat-transfer coefficient for the tube.
4. Assume an outer tube surface temperature.

5. Compute the outside condensing coefficient using properties evaluated at the film temperature.

6. Compute the outer surface temperature and iterate steps 5 and 6 if not within 1%.

7. Assume a viscosity-correction factor for the Sieder-Tate equation of 1.0.

8. Compute the inside heat-transfer coefficient.

9. Compute the inner surface temperature.

10. Compute the viscosity correction factor and iterate steps 8 through 10 if not within 1%.

11. Compute the Sieder-Tate coefficient and iterate steps 2 through 11 if not within 0.5%.

C. PROGRAM DRP

1. Compute the average cooling water temperature.
2. Compute the cooling water velocity.
3. Compute the mass-flow rate of the cooling water.
4. Compute the heat transferred to the water.
5. Compute the log-mean-temperature difference.
6. Compute the overall heat-transfer coefficient.
7. Compute the wall resistance of the tube.
8. Compute the Reynolds number of the cooling water.
9. Compute the inside heat-transfer coefficient.
10. Compute the condensing heat-transfer coefficient.

V. RESULTS AND DISCUSSION

Numerous data runs were made using the procedure described in Section II.G. Time constraints, however, limited the number of repeat runs that could be made for this thesis. Primary concern focused on establishing a reliable, repeatable Sieder-Tate coefficient. Data were taken for all of the tubes at both atmospheric and vacuum (88mm Hg, 1.7 psia) conditions. Complete filmwise condensation was maintained for all data runs, and the mass concentration of noncondensable gases was held between 0% and -1% during all testing. The negative value was indicative of slight superheat in the system or an inaccurate manometer reading.

A. INSIDE HEAT TRANSFER COEFFICIENT

1. Instrumented Tube Results

Figure 5.1 shows the variation of the Nusselt number as a function of the Sieder-Tate parameter for the instrumented tube run at atmospheric pressure (run SDA7). This method yielded a Sieder-Tate coefficient of 0.035 on two separate data runs (SDA7 and SDA8). The same method under vacuum conditions yielded a coefficient of 0.037, which was also repeated (runs SDA5 and SDA6). The temperature distribution around the tube wall was symmetrical about the vertical plane passing downward through the centerline of the tube, and showed as much as a 16 °C temperature drop from the top of the tube to the bottom.

2. Smooth Tube Results

Figure 5.2 shows the modified Wilson Plot for smooth-tube data collected at atmospheric pressure (run

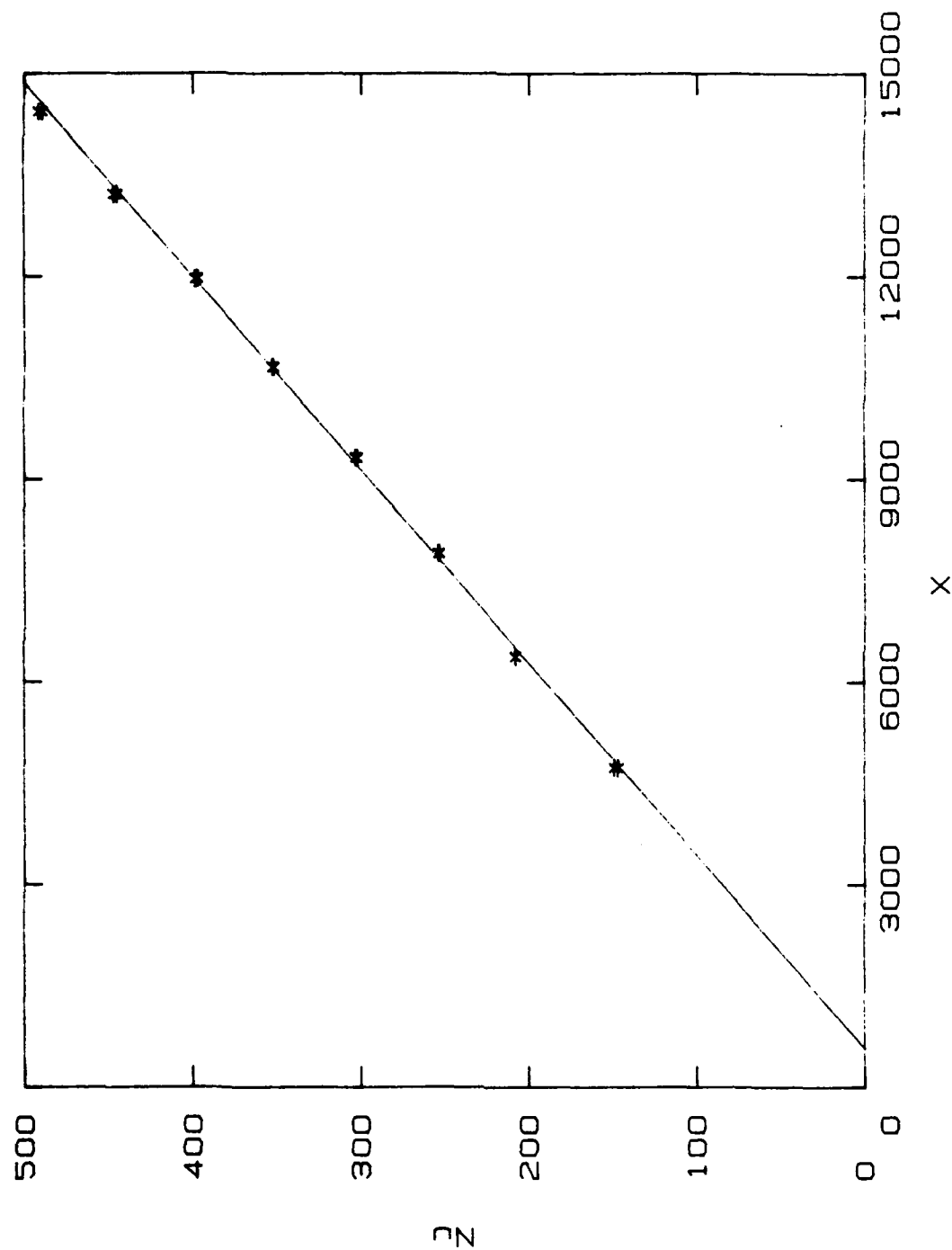


Figure 5.1 Inside Nusselt number plot for the instrumented tube.

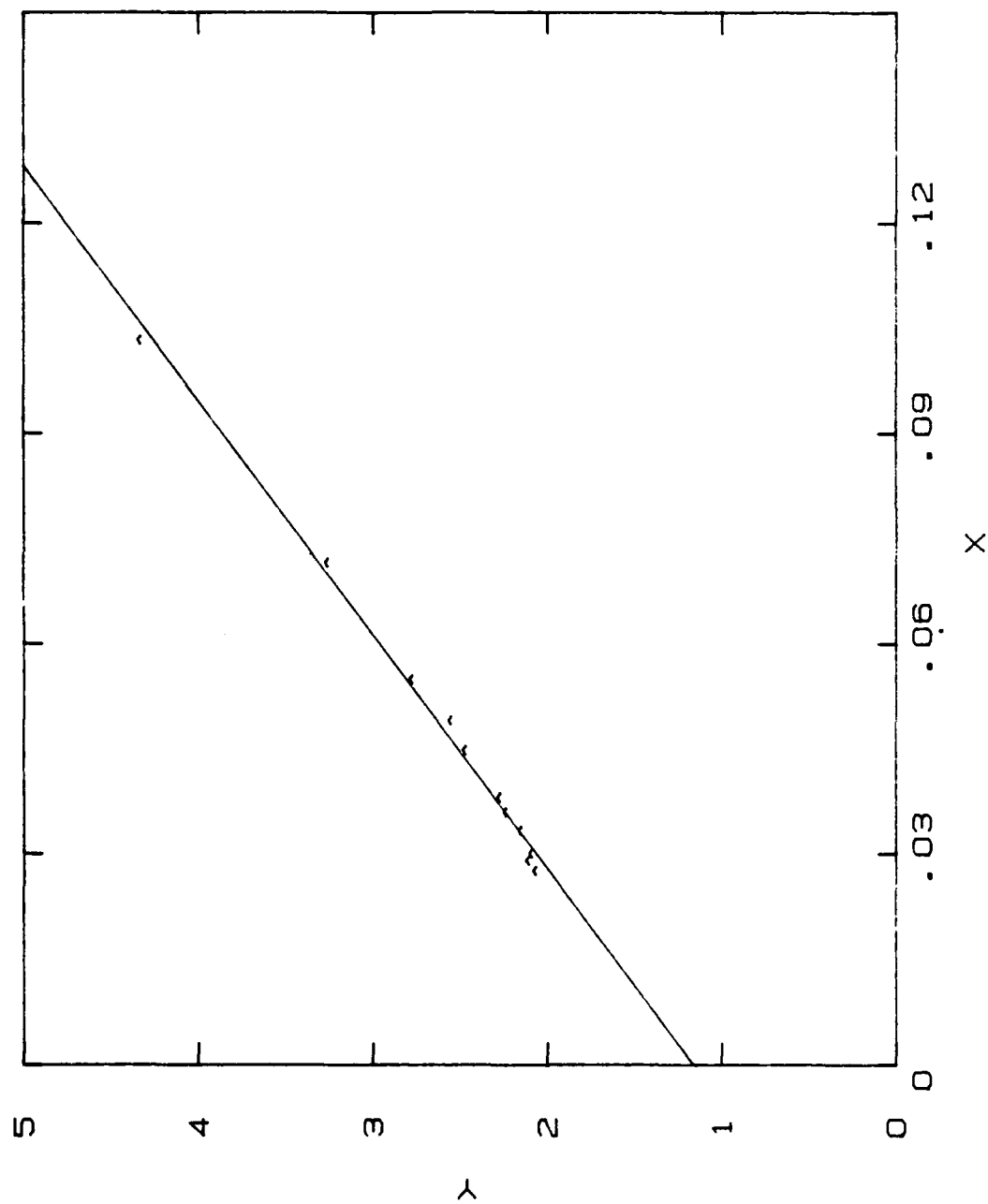


Figure 5.2 Wilson plot for the smooth tube.

OD12). This method produced a Sieder-Tate coefficient of 0.033 with an intercept of 1.16. A similar plot for vacuum conditions (run OD10) produced a coefficient of 0.036 and an intercept of 1.27. The Nusselt theory predicts an intercept of 1.53 but, as was noted in Section III.C., a finite vapor velocity past the tube was unavoidable in this research.

Figure 5.3 shows a plot of the Fujii [Ref. 10] correlation for the smooth-tube runs. This experimental correlation is to correct the Nusselt number for the effects of vapor shear on the test tube and is a plot of the equation:

$$\widetilde{NuRe}^{-1/2} = 0.96F^{1/5}$$

The results obtained were slightly higher than those predicted using this correlation.

3. Discrepancies

The original Sieder-Tate equation [Ref. 11] for fully developed turbulent flow in a tube with an L/D ratio greater than 60 has a leading coefficient of 0.027, so a higher value for the shorter tube (L/D = 18) used for this research stands to reason. The data for the tubes appears at first inconsistent, with results of 0.033, 0.035, 0.036, and 0.037 - showing up to a 6% scatter from the mean. Both tubes, however, showed a larger coefficient when the test section pressure was reduced, which reduced the heat flux as well. Dropping the pressure from atmospheric to a high vacuum (88 mm Hg, 1.7 psia) reduced the heat flux by a factor of almost three [Fig. 5.4]. Stated another way, a low heat flux produced coefficients of 0.036 and 0.037, while a higher heat flux produced 0.033 and 0.035.

The author doubts the reliability of the inside coefficient obtained under vacuum conditions for two reasons:

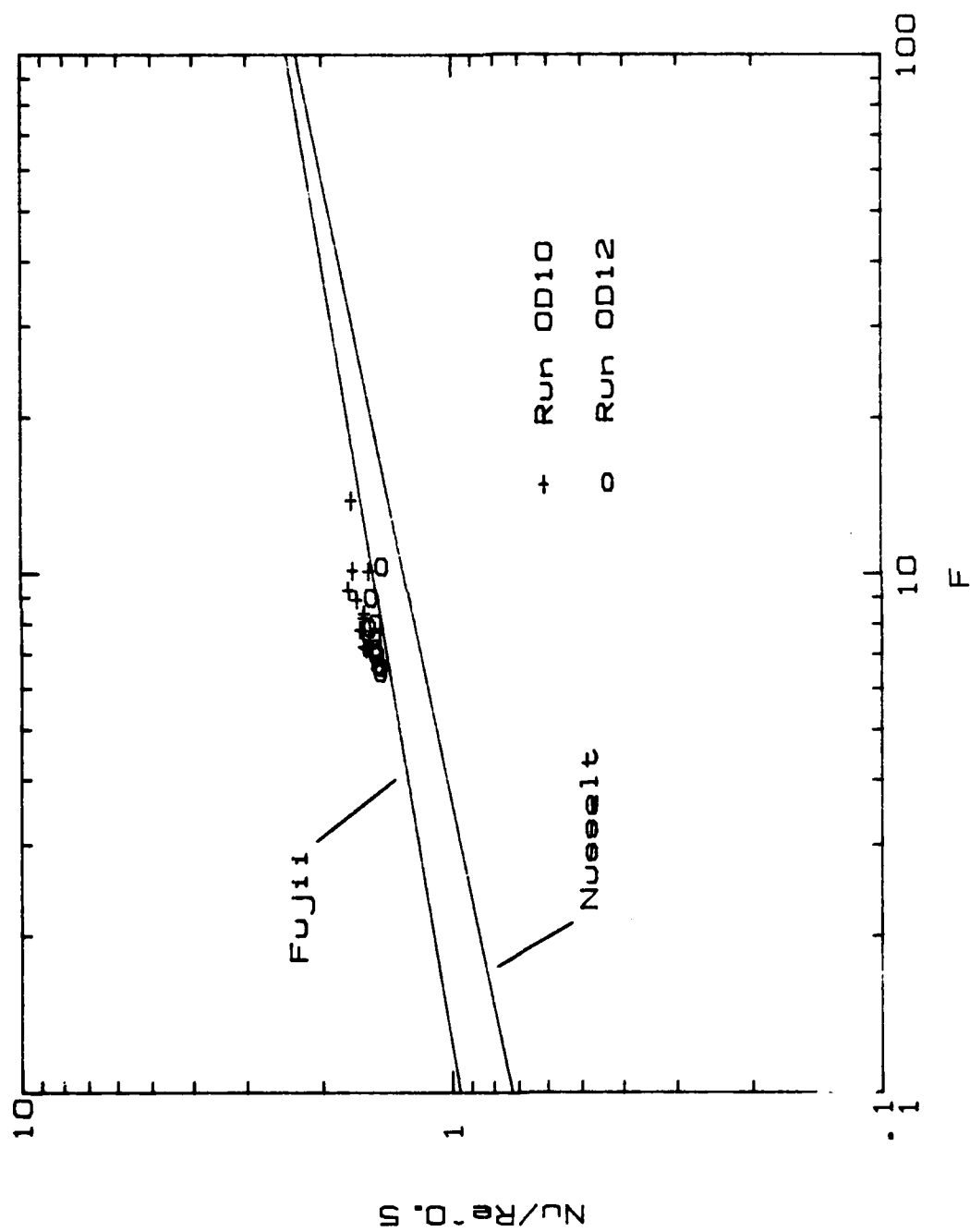


Figure 5.3 Fujii correlation [Ref. 10] for smooth-tube data.

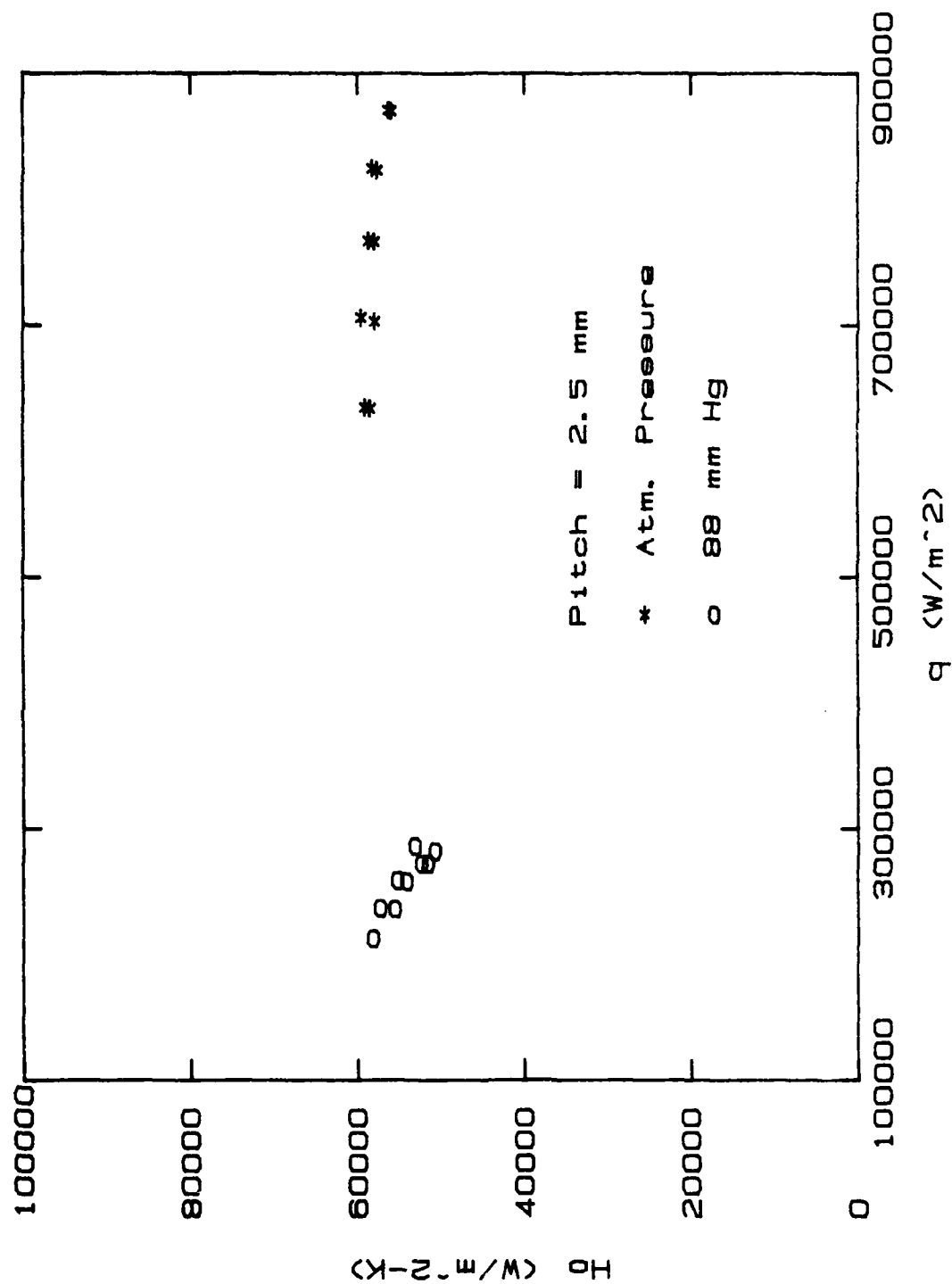


Figure 5.4 Relative heat fluxes for atmospheric and vacuum runs.

First, reducing the flow rate through the tube lowers the heat flux and increases the inside convective thermal resistance. Since the condensing coefficient is inversely proportional to the heat flux raised to the one-third power, the outside condensing resistance decreases. Because of this, the inside resistance becomes the dominant factor in the overall thermal resistance of the tube. Any error in measuring the inside heat transfer coefficient will greatly amplify the computed error in the condensing resistance. Thus, the condensing coefficient is highly sensitive to the accuracy of the inside coefficient, particularly at low water velocities (and corresponding heat fluxes).

Second, the test apparatus was subject to radio-frequency (RF) interference from the power supply. As the power was cut back to lower the heat flux, the silicon controlled rectifier chopped the input signal proportionally and emitted the chopped portion as RF energy. Despite efforts to shield the cabling to the data-acquisition system, it still captured the RF signal with unacceptable results, and the thermopile was experiencing instantaneous fluctuations of several hundred microvolts. Increasing the power supply, however, decreased the errant signal until, at the maximum power input used for the high heat flux measurements, the thermopile showed a near-steady temperature difference that was within 0.1°C of the quartz thermometer.

For these reasons, the Sieder-Tate coefficients obtained from the low heat-flux runs were discarded. Averaging the coefficients found from both measurements for the high heat flux case yielded a coefficient of 0.034 ± 0.001 .

B. FINNED TUBES

Figure 5.5 shows a relative plot of the outside condensing coefficient for all six finned tubes compared with smooth tube results and the Nusselt line. Figure 5.6 shows the same results corrected for area increases due to finning. These data were computed using the leading coefficient on the inside of 0.034 obtained in the previous section.

All tubes tested show good enhancement over the smooth tube. Notice the increase of the smooth tube over the Nusselt line - a result of the inherent vapor shear in the test section. The increased scatter in the lower heat-flux range is again a function of the increased significance of errors in measuring the inside thermal resistances. The plotting program used neglected ordinate values below zero or greater than 10^5 , so the scattering in this portion of the plot is actually worse than it appears. Figure 5.7 is a plot of the values obtained for the outside heat transfer coefficients of the six finned tubes for a constant heat flux of $250,000 \text{ W/m}^2$ ($79,000 \text{ Btu/hr-ft}^2$) and a pressure of 88 mm Hg (1.7 psia). This plot more clearly shows the optimum pitch of 2.5 mm.

The heat-transfer characteristics for any tube will be enhanced by the addition of fins. In the case of purely convective heat transfer, the enhancement is a function of the increased surface area exposed to the fluid medium.

Filmwise condensation, however, is dissimilar in that the build-up of a condensate film acts as an additional thermal resistance for the heat-transfer process. The objective of tube enhancement, therefore, is to decrease this film thickness. The surface tension forces in the condensate tend to draw the liquid toward the fins, leaving the tube surface with a thinner film. The thinner film results in a higher heat-transfer coefficient. [Ref. 12].

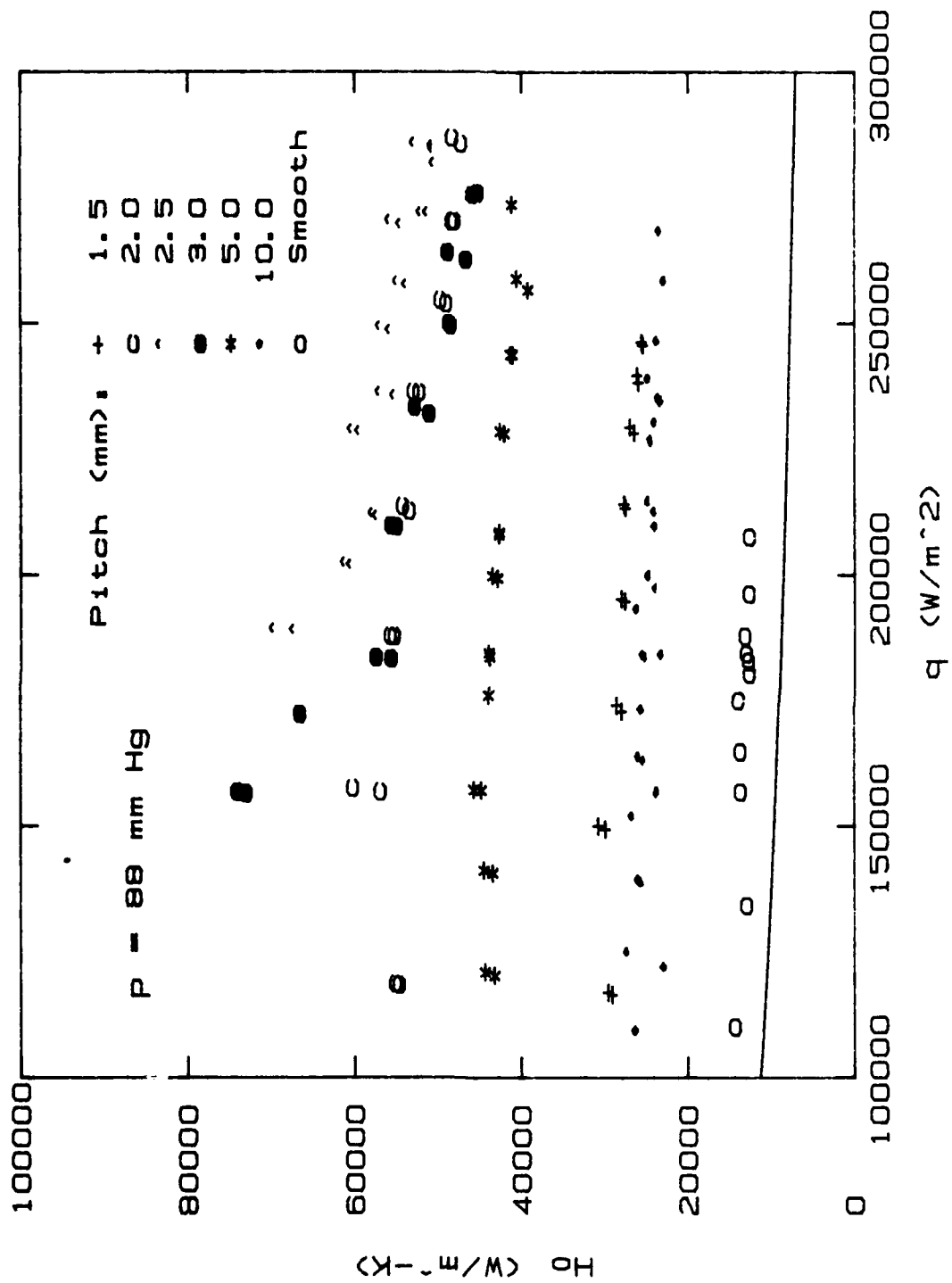


Figure 5.5 Comparison of finned tubes with smooth-tube performance.

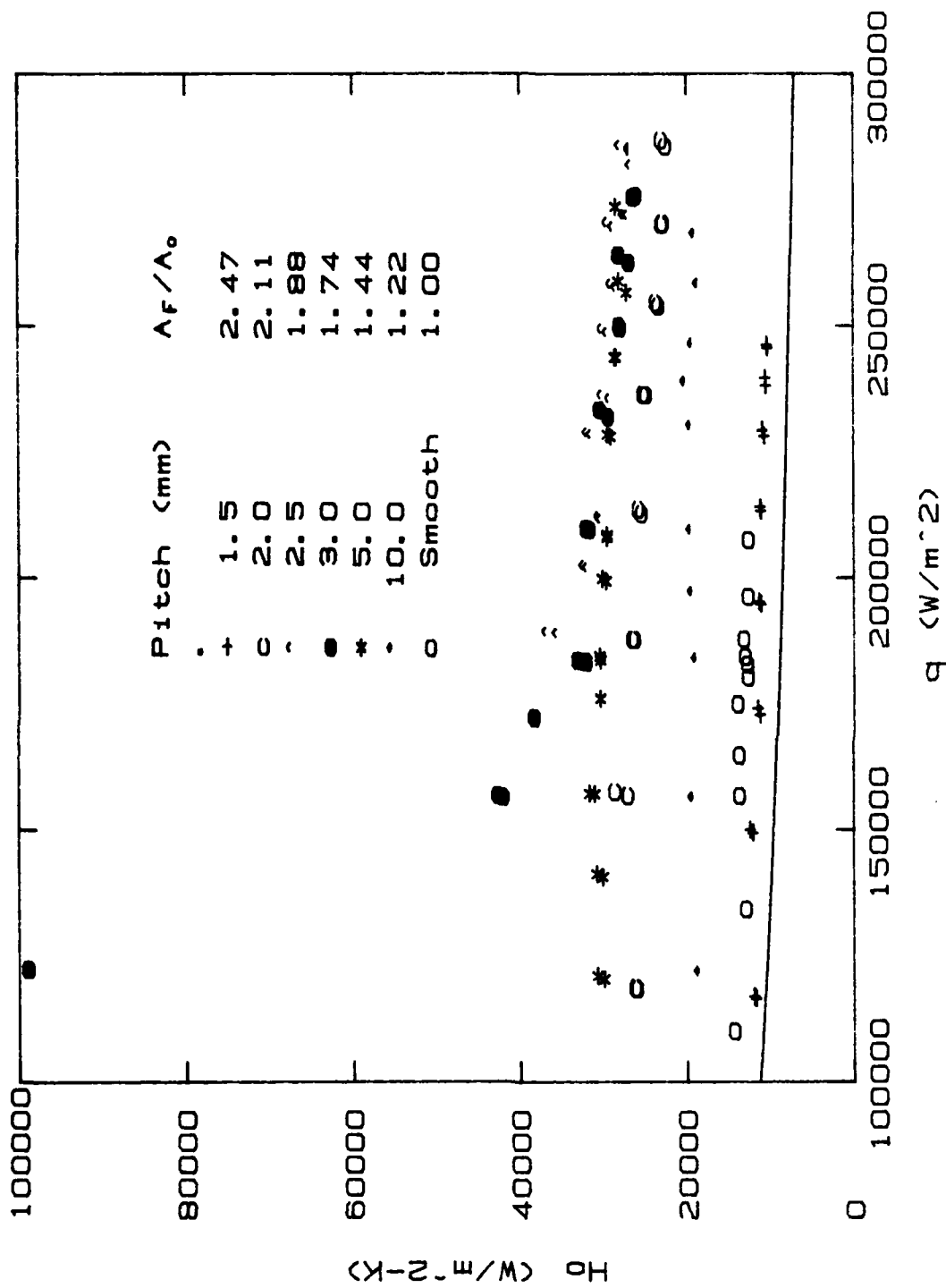


Figure 5.6 Outside condensing coefficients corrected for area.

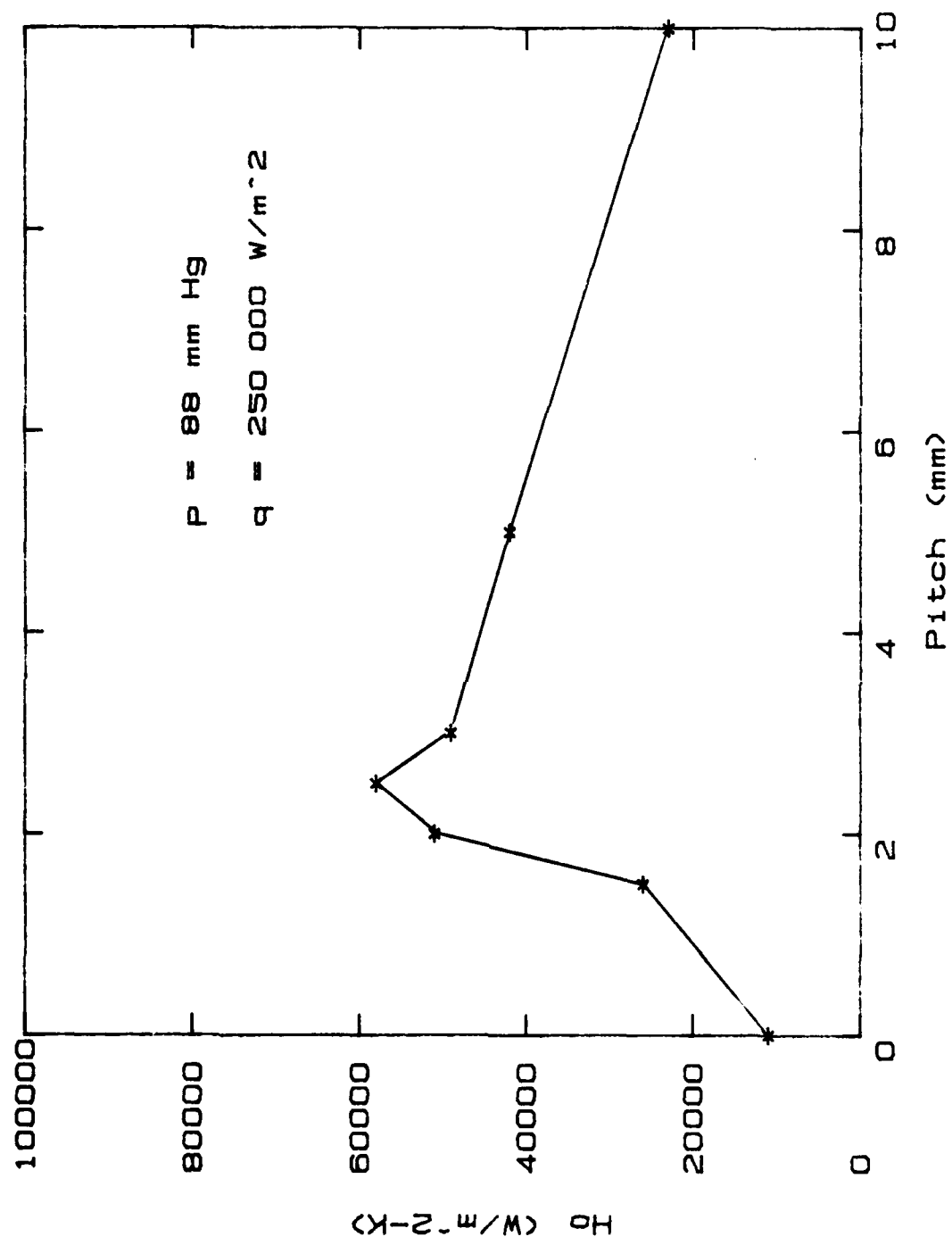


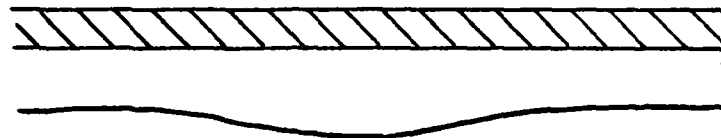
Figure 5.7 Variation of condensing coefficient with fin pitch.

The optimum pitch found in this research increases the surface of the condenser tube 88%, but condensing heat-transfer coefficients for that pitch were enhanced by as much as 330%.

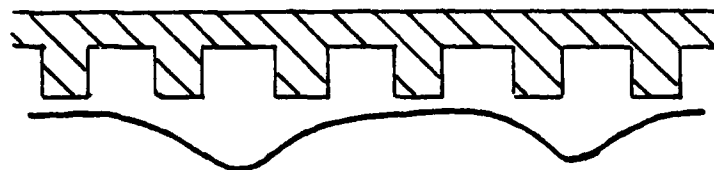
The optimum pitch serves as the right trade-off between the attractive forces of the fins on the condensate and the channel area between the fins to drain the condensate from the tube. A pitch smaller than the optimum has too narrow a gap between fins to efficiently allow condensate run-off. This is because the condensate drawn to adjacent fins only combines to create a thicker film as shown in Figure 5.8.



Smooth Tube



Optimum Pitch



Pitch Too Small

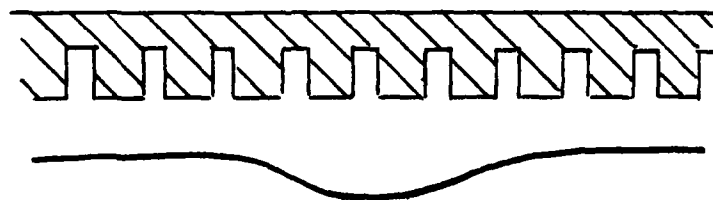


Figure 5.8 Sketch of the effect of finning on condensation.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. The test apparatus successfully operates under vacuum conditions with no degrading effects caused by the presence of noncondensable gases.

2. The Sieder-Tate coefficient was determined to be 0.034 ± 0.001 using both an instrumented smooth tube and the modified Wilson plot technique.

3. An optimum fin pitch of 2.5 mm was found for the finned tubes tested.

4. Heat-transfer enhancements up to 300% were realized while the increase in the tube outer surface area (due to finning) was only 88% over the smooth tube.

B. RECOMMENDATIONS

1. Install a second, more reliable pressure transducer to replace the manometer.

2. Install a larger cooling-water sump to eliminate use of the once-through system from the fresh-water tap.

3. Collect data using an insert for the test tube to decrease the internal convective resistance and, thereby, decrease the uncertainty in the calculated condensing coefficient.

4. Take data for the finned tubes while varying fin height and thickness (as well as pitch).

APPENDIX A
THERMOCOUPLE CALIBRATION

1. EQUIPMENT USED

a. Thermocouple Wire

Copper-constantan, 0.245-mm (0.01-in) Teflon-coated wire was used for all thermocouples.

b. Calibration bath

A Rosemont Engineering Model 913A calibration bath was used. A schematic representation of the bath is shown in Figure A.1.

1) Heating: Electrical

2) Cooling: Liquid Nitrogen

Note: Once a desired temperature is reached, the temperature is held constant by rapid cycling between heating and cooling. The bath is rated for temperature fluctuations of less than 0.01°C.

c. Thermocouple readout

An HP 3054A Data Acquisition/Control System was used to obtain data. Resolution of the acquisition system was 1 μ V.

d. Bath temperature measurement

A platinum resistance thermometer with an accuracy of 0.01 C was used.

2. PREPARATION

a. Procedure

The instrumented tube (with the wall thermocouples installed) and the steam thermocouples were immersed in the bath as well as the probes for the quartz thermometer.

b. Analysis

The computer program TCAL was used to monitor and store all thermocouple readings on a disk. A listing of the program is located in Appendix E.

3. CALIBRATION PROCEDURE

- a. The bath temperature was set at about 10 °C.
- b. When the bath temperature reached steady state, its value was entered into the computer.
- c. The computer automatically recorded and printed all thermocouple readings.
- d. The bath temperature was raised in increments of 10 C to 90 °C and steps b and c were repeated for each increment.

4. CALIBRATION CURVES

- a. A least-squares method was used to generate a polynomial of the form:

$$D_T = a_0 + a_1 T + a_2 T^2$$

where: D_T is the difference between the bath and thermocouple temperatures, and

T is the value of the thermocouples obtained using the seventh-order polynomial fitted for the Type T thermocouple wire used. This polynomial is listed in the beginning of the program TCAL.

- b. Coefficient values obtained were:

$$a_0 = 4.7338 \times 10^{-3}$$

$$a_1 = 7.6928 \times 10^{-3}$$

$$a_2 = -8.0779 \times 10^{-5}$$

- c. A plot of the curves is found in Figure A.1. The curve for the wall thermocouples gives a different reading due to the thermal conduction of the air temperature through the tube. The data used for calibration did not include this average value. Only the value obtained for the two steam thermocouples was used for all of the thermocouples.

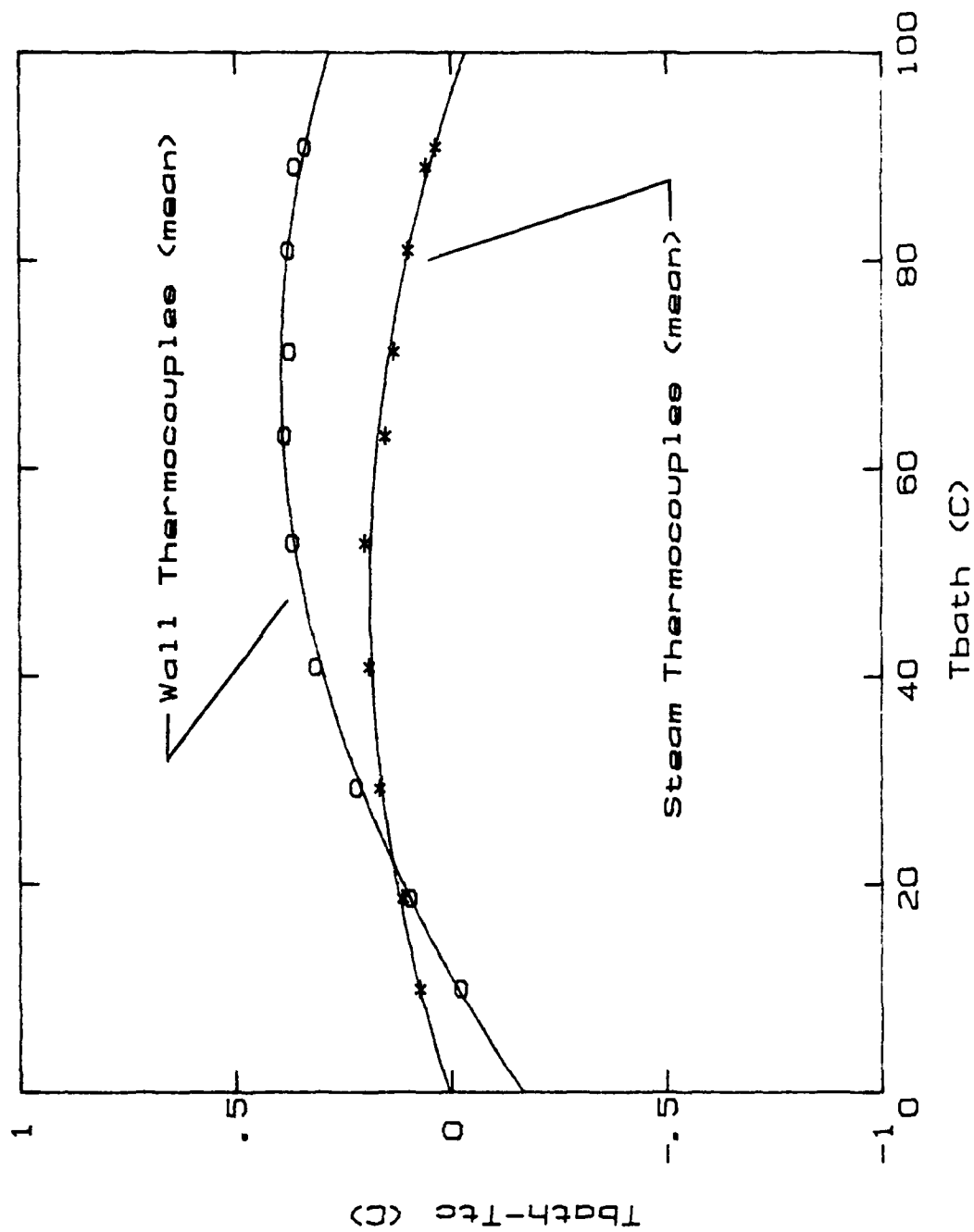


Figure A.1 Calibration curve for the thermocouples.

APPENDIX B
SAMPLE CALCULATIONS

1. HEAT LOSS

A set of calculations was performed to estimate the heat loss of the apparatus due to natural convection. These calculations were performed for two main sections: the boiler (with and without insulation) and the piping to the test section. The minimum power input used during the thesis was 17 kW.

a. Boiler (without insulation)

1) Given the following dimensions and properties of the boiler section:

$$r_{i,B} = 0.1524 \text{ m}$$

$$r_{o,B} = 0.1561 \text{ m}$$

$$L_B = 0.4064 \text{ m}$$

$$k_C = 1.4 \text{ W/m-K}$$

2) Given the following temperatures:

$$T_{i,B} = 100^\circ\text{C}$$

$$T_{o,B} = 95^\circ\text{C}$$

$$T_\infty = 25^\circ\text{C}$$

$$T_f = (95+25)/2 = 60^\circ\text{C}$$

3) Given the following properties of air at the film temperature:

$$k_A = 28.74 \times 10^{-3} \text{ W/m-K}$$

$$Pr = 0.702$$

$$\nu = 19.21 \times 10^{-6} \text{ m}^2/\text{s}$$

$$\beta = 0.003 \text{ K}^{-1}$$

- 4) Compute the Grashof Number for the boiler assuming laminar conditions ($Ra < 10^9$):

$$Gr_g = g\beta(T_{o,g} - T_{\infty})L^3/\nu^2$$

$$Gr_g = 3.7 \times 10^8$$

- 5) Compute the Rayleigh Number for the boiler:

$$Ra_g = Gr Pr$$

$$Ra_g = 2.6 \times 10^8 \quad (< 10^9)$$

- 6) Determine the applicability of a flat-plate analysis according to the method of Sparrow and Gregg [Ref. 13]

$$L/r_{o,g} < (0.15/\sqrt{8}) Gr^{1/4}$$

$$2.60 < 7.36$$

- 8) Compute the average Nusselt Number (via flat-plate analysis):

$$\overline{Nu} = [0.825 + 0.387 Ra_g^{1/4} / [1 + (0.492/Pr)^{9/16}]^{4/27}]^2$$

$$\overline{Nu} = 81.3$$

- 9) Compute the external heat-transfer coefficient:

$$\bar{h}_o = \overline{Nu} k / L$$

$$\bar{h}_o = 5.75 \text{ W/m}^2\text{-K}$$

- 10) Compute the external convective thermal resistance:

$$R = 1/(\bar{h}_o 2\pi r_{o,g} L_g)$$

$$R = 0.436 \text{ K/W}$$

- 11) Calculate the wall resistance:

$$R_w = \ln(r_{o,s}/r_{i,s}) / 2\pi k_c L_s$$

$$R_w = 0.007 \text{ K/W}$$

12) Neglecting the wall resistance, calculate the heat loss from the boiler:

$$Q_B = (T_{i,s} - T_a) / (R + R_w)$$

$$Q_B = 169.3 \text{ W}$$

b. Boiler (with insulation)

$$Q'_B = 29.2 \text{ W}$$

c. Piping

$$Q_P = 65.0 \text{ W}$$

d. Total (worst case)

$$Q = Q_B + Q_P$$

$$Q = 234.3 \text{ W} \quad (<< 17000 \text{ W of input power})$$

APPENDIX C

STEAM-CLEANING PROCEDURE

Note: The procedures listed here provide an excellent method of cleaning the apparatus, but will cause the walls of the apparatus to heat to temperatures over 100 C (212 F). Once this happens, several hours are required before the walls can cool down such that they won't superheat the steam generated during an experimental run. Therefore, use this method only prior to operating at atmospheric pressure or when the system is badly contaminated.

1. Ensure the water level in the boiler is at least six inches above the upper ends of the heaters.
2. Remove the thermopile from the inlet side of the test section.
3. Energize the power supply and adjust the rheostat until the voltmeter reads about 100 V.
4. Close the recirculating valve.
5. Open the fill/drain valve.
6. Once vapor begins exiting the fill/drain line, allow the system to steam for several minutes.
7. To maximize the steam flow through the test section, fully open the throttle to the auxiliary condenser.
8. When done, simultaneously close the drain/fill valve and open the recirculating valve.
9. Circulate cooling water through the test tube and check for the presence of any dropwise condensation.
10. Reinstall the thermopile.

APPENDIX D
SYSTEM START-UP AND SHUT-DOWN PROCEDURES

To start the system:

1. Fill the boiler to at least six inches above the upper level of the heaters.
2. Energize the air ejector for ten minutes.
3. Circulate water through the cooling water sump by opening the inlet valve and activating the siphon.
4. Energize the power to the boiler and adjust the rheostat until the voltmeter reads 90 V for vacuum operation, or 170 V for atmospheric pressures.
5. Energize the circulating pumps and adjust the throttle for the desired flow through the tube.
6. Open the valve to the auxiliary condenser and adjust the flow: about 15% for vacuum operation or 30% for atmospheric runs.
7. Observe the steam temperature indicated on the front of the data acquisition unit until the voltage is reached corresponding to the saturation temperature of the the desired operating pressure.
8. Energize the air ejector for two minutes.
9. Adjust the the flow rate through the auxiliary condenser to bring the apparatus to the desired operating pressure.

To secure the system:

1. Secure cooling water to the test tube.
2. Secure power to the boiler.
3. Open the vent valve.
4. Secure the water supply to the auxiliary condenser.

APPENDIX E
COMPUTER PROGRAM LISTINGS

The following pages contain the computer program listings used for this thesis:

SIEDER (page 61)

WILSON (page 65)

DRP (page 71)

TCAL (page 80)

PROGRAM SIEDER

```

1000! FILE NAME: SIEDER
1010! DISK NUMBER: 12
1020! REVISED: November 29, 1983
1030!
1040 COM /Cc/ C(7)
1050 DIM Emf(10),Tw(5)
1060 DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1070 DATA -9247486589,6.97688E11,-2.66192E13,3.94078E14
1080 READ C(*)
1090 Kcu=385
1100 Di=.0127
1110 Do=.01905
1120 Dr=.015875
1130 L=.13335
1140 L1=.060325
1150 L2=.034925
1160 PRINTER IS 701
1170 BEEP
1180 CLEAR 709
1190 INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Bs
1200 OUTPUT 709;"TD";Bs
1210 Series:
1220 OUTPUT 709;"TD"
1230 ENTER 709:AS
1240 PRINT USING "10X, ""Month, date and time: "",14A";AS
1250 BEEP
1260 INPUT "ENTER DISK NUMBER",Dn
1270 PRINT
1280 PRINT USING "10X, ""NOTE: Program name: SIEDER""
1290 PRINT USING "16X, ""Disk number = "",DD";Dn
1300 BEEP
1310 INPUT "ENTER INPUT MODE (1=3054A.2=FILE)",Im
1320 IF Im=1 THEN
1330 BEEP
1340 INPUT "GIVE A NAME FOR THE DATA FILE",D_files$
1350 CREATE BDAT D_files$.10
1360 ELSE
1370 BEEP
1380 INPUT "GIVE THE NAME OF THE DATA FILE",D_files$
1390 BEEP
1400 INPUT "ENTER THE NUMBER OF RUNS STORED",Nrun
1410 PRINT USING "16X, ""This analysis was performed for file "",10A";D_files$
1420 END IF
1430 BEEP
1440 INPUT "GIVE A NAME FOR PLOT DATA FILE",Plots$
1450 BEEP
1460 INPUT "ENTER OPTION FOR END-FIN EFFECT (1=Y,0=N)",Ife
1470 IF Ife=0 THEN PRINT USING "16X, ""This analysis neglects end-fin effect""
1480 IF Ife=1 THEN PRINT USING "16X, ""This analysis includes end-fin effect""
1490 CREATE BDAT Plots$.5
1500 ASSIGN @File TO D_files$
1510 ASSIGN @Filep TO Plots$
1520 J=0
1530 Sx=0
1540 Sy=0
1550 Sxs=0
1560 Sxy=0
1570 IF Im=1 THEN
1580! READ DATA THROUGH THE DATA ACQUISITION SYSTEM

```

```

1590! IF THE INPUT MODE (Im) = 1
1600 BEEP
1610 INPUT "ENTER FLOWMETER READING".Fm
1620 OUTPUT 709:"AR AF20 AL30 VR1"
1630 FOR I=0 TO 10
1640 OUTPUT 709:"AS SA"
1650 IF I>4 THEN
1660 Se=0
1670 FOR K=0 TO 19
1680 ENTER 709:E
1690 Se=Se+E
1700 NEXT K
1710 Emf(I)=ABS(Se/20)
1720 ELSE
1730 ENTER 709:E
1740 Emf(I)=ABS(E)
1750 END IF
1760 NEXT I
1770 OUTPUT 713:"T1R2E"
1780 WAIT 2
1790 ENTER 713:T11
1800 OUTPUT 713:"T2R2E"
1810 WAIT 2
1820 ENTER 713:T2
1830 OUTPUT 713:"T1R2E"
1840 WAIT 2
1850 ENTER 713:T12
1860 T1=(T11+T12)*.5
1870 ELSE
1880! READ DATA FROM A USER-SPECIFIED FILE IF
1890! INPUT MODE (Im) = 2
1900 ENTER @File;Emf(*),T1,T2,Fm
1910 END IF
1920 Tavg=(T1+T2)*.5
1930 Twall=0
1940 FOR I=5 TO 10
1950 Tw(I-5)=FNTvsv(Emf(I))
1970 Twall=Twall+Tw(I-5)
1980 NEXT I
1990 Twall=Twall/6
2000 Cpw=FNCpw(Tavg)
2010 Rhov=FNRRhov(Tavg)
2020 Md=5.00049E-3+6.9861937E-3*Fn
2030 Md=Md*(1.0365-1.96644E-3*T1+5.252E-6*T1^2)/.995434
2040 Mf=Md/Rhov
2050 Vw=Mf/(PI*D1^2/4)
2051 T2c=T2-(.0138+.001*Vw^2)
2060! T2c=T2-.004*Vw^2
2070 Q=Md*Cpw*(T2c-T1)
2080 Dtw=Q*LOG(Do/D1)/(2*PI*Kcu*L)*.5
2090 Twall=Twall-Dtw
2100 Lmtd=(T2c-T1)/LOG((Twall-T1)/(Twall-T2c))
2110 Kw=FNKw(Tavg)
2120 P1=PI*(D1+Do)
2130 P2=PI*(D1+Dr)
2140 A1=(Do-D1)*PI*Do
2150 A2=(Dr-D1)*PI*Dr
2160 H1=Q/(PI*D1*L=Lmtd)
2170 IF Ife=0 THEN
2180 H1c=H1
2190 GOTO 2300

```

```

2200 END IF
2210 M1=(H1*P1/(Kcu*A1))^.5
2220 M2=(H1*P2/(Kcu*A2))^.5
2230 Fe1=FNTanh(M1*L1)/(M1*L1)
2240 Fe2=FNTanh(M2*L2)/(M2*L2)
2250 Hic=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Lmtd)
2260 IF ABS((H1-Hic)/Hic)>.01 THEN
2270 Hi=(Hic+H1)*.5
2280 GOTO 2210
2290 END IF
2300 PRINT
2310 PRINT USING "10X,""Position number          : 1      2      3      4      5
6""
2320 PRINT USING "10X,""Wall temperature (Deg C) : ""',6(DD.DD,iX)":Tw(*)
2330! CALCULATE THE NUSSELT NUMBER
2340 Nu=Hic*Di/Kw
2350 Muw=FNMuw(Tavg)
2360 Re=Rhow*Vw*Di/Muw
2370 Cf=(Muw/FNMuw(Twall))^.14
2380 Prw=FNPrw(Tavg)
2390 X=Re^.8*Prw^.3333*Cf
2400! COMPUTE COEFFICIENTS FOR THE LEAST-SQUARES-FIT
2410! STRAIGHT LINE
2420 OUTPUT @File;X,Nu
2430 PRINT USING "10X,""Twall  Tin  Tout  Lmtd  Vw  X  Nu""
2440 PRINT USING "10X,4(2D.2D,2X),Z.DD,2X.5D.D,2X.4D.D";Twall,T1,T2c,Lmtd,Vw,X,
Nu
2450 Sx=Sx+X
2460 Sy=Sy+Nu
2470 Sxs=Sxs+X*X
2480 Sxy=Sxy+X*Nu
2490! STORE RAW DATA IN A USER-SPECIFIED FILE IF
2500! INPUT MODE (Im) = 1
2510 IF Im=1 THEN OUTPUT @File;Emf(*),T1,T2,Fm
2520 BEEP
2530 J=J+1
2540 IF Im=1 THEN
2550 INPUT "ARE YOU TAKING MORE DATA (1=YES.0=NO)?",Go_on
2560 Nrun=J
2570 IF Go_on=1 THEN 1570
2580 ELSE
2590 IF J<Nrun THEN 1570
2600 END IF
2610! Ci=Sxy/Sxs
2620 Ci=(Nrun*Sxy-Sy*Sx)/(Nrun*Sxs-Sx^2)
2630 Ac=(Sy-Ci*Sx)/Nrun
2640 PRINT
2650 PRINT USING "10X,""Sieder-Tate Coefficient = ""',D.4D";Ci
2660 PRINT
2670 PRINT USING "10X,""Least-Squares Line: ""
2680 PRINT USING "12X,""Slope = ""',MD.5DE,"";Ci
2690 PRINT USING "12X,""Intercept = ""',MD.5DE,"";Ac
2691 PRINT
2700 IF Im=1 THEN
2720 BEEP
2730 PRINT USING "10X,""NOTE: ""',ZZ,"" data runs were stored in file ""',8A";Nru
n.D_files
2731 ELSE
2732 PRINT USING "10X,""NOTE: The above analysis was performed for file ""',14A"
;D_files

```

```

2740 END IF
2750 PRINT USING "16X."""Plot data are stored in file """,14A":Plot$
2760 ASSIGN @File TO *
2770 ASSIGN @Filep TO *
2780 END
2790 DEF FNRhow(T)
2800 Ro=1006.35724-T*(.774489-T*(2.262459E-2-T*3.03304E-4))
2810 RETURN Ro
2820 FNEND
2830 DEF FNPw(T)
2840 Pw=FNCpw(T)*FNMw(T)/FNkw(T)
2850 RETURN Pw
2860 FNEND
2870 DEF FNMw(T)
2880 A=247.8/(T+133.15)
2890 Mw=2.4E-5*10^A
2900 RETURN Mw
2910 FNEND
2920 DEF FNkw(T)
2930 Kw=.572183504477+1.52770121209E-3*T
2940 RETURN Kw
2950 FNEND
2960 DEF FNTvsv(Emf)
2970 COM /Cc/ C(7)
2980 Sum=C(0)
2990 FOR I=1 TO 7
3000 Sum=Sum+C(I)*Emf^I
3010 NEXT I
3020 RETURN Sum
3030 FNEND
3040 DEF FNCpw(T)
3050 Cpw=(4.21120858-T*(2.26826E-3-T*(4.42361E-5+T*2.71428E-7)))*1000
3060 RETURN Cpw
3070 FNEND
3080 DEF FNTanh(X)
3090 P=EXP(X)
3100 Q=EXP(-X)
3110 Tanh=(P+Q)/(P-Q)
3120 RETURN Tanh
3130 FNEND

```

PROGRAM WILSON

```

1000! FILE NAME: WILSON
1010! REVISED: December 5, 1983
1020!
1030 COM /Cc/ C(7)
1040 DATA 0.10086091,25727.94369,-767345.3295,78025595.81
1050 DATA -9247486589.6,97688E11,-2.66192E13,3.94078E14
1060 READ C(*)
1070 DIM Emf(4)
1080 L=.130175
1090 L1=.060325
1100 L2=.034925
1110 Do=.01905
1120 Di=.0127
1130 Dr=.015785
1140 Kcu=395
1150 Rm=Do*LOG(Do/Di)/(2*Kcu)
1160 PRINTER IS 701
1170 BEEP
1180 CLEAR 709
1190 INPUT "ENTER MONTH, DATE, AND TIME (MM:DD:HH:MM:SS)".BS
1200 OUTPUT 709;"TD";BS
1210 Jp=0
1220 OUTPUT 709;"TD"
1230 ENTER 709:AS
1240 PRINT USING "10X, ""Month, date and time : "",14A":AS
1250 BEEP
1260 INPUT "ENTER DISK NUMBER",Dn
1270 PRINT
1280 PRINT USING "10X, ""NOTE: Program name : M_WILSON""
1290 PRINT USING "16X, ""Disk number = "",DD":Dn
1300 BEEP
1310 INPUT "ENTER INPUT MODE (1=3054A,2=FILE)",Im
1320 IF Im=1 THEN
1330 BEEP
1340 INPUT "GIVE A NAME FOR THE DATA FILE",D_files
1350 CREATE BDAT D_files,10
1360 ELSE
1370 BEEP
1380 INPUT "GIVE THE NAME OF THE DATA FILE",D_files
1390 PRINT USING "16X, ""This analysis is for data in file "",14A":D_files
1400 BEEP
1410 INPUT "ENTER THE NUMBER OF RUNS STORED".Nrun
1420 END IF
1430 BEEP
1440 INPUT "GIVE A NAME FOR PLOT-DATA FILE",Plots
1450 BEEP
1460 INPUT "ENTER OPTION (1-QCT,2-T-PILE,3-AVE)",Itm
1470 BEEP
1480 INPUT "ENTER OPTION FOR END-FIN EFFECT (1-Y,0-N)".Ifc
1490 IF Itm=1 THEN PRINT USING "16X, ""This analysis uses QCT readings""
1500 IF Itm=2 THEN PRINT USING "16X, ""This analysis uses T-PILE readings""
1510 IF Itm=3 THEN PRINT USING "16X, ""This analysis uses average of QCT and T-P
ILE readings""
1520 IF Ifc=1 THEN PRINT USING "16X, ""This analysis includes end-fin effect""
1530 IF Ifc=0 THEN PRINT USING "16X, ""This analysis neglects end-fin effect""
1540 CREATE BDAT Plots,10
1550 ASSIGN @Filep TO Plots
1560! Ciu=.040
1570! Cil=.028

```

```

1580 Jj=0
1590 Ci=.03
1600 J=0
1610! Ci=(Ciu+Cil)*.5
1620 Sx=0
1630 Sy=0
1640 Sxs=0
1650 Sxy=0
1660 PRINT
1670 PRINT USING "10X, ""Iteration number          = "",DD":Jj+1
1680 IF Jj=0 OR Jp=1 THEN
1690 PRINT
1700 PRINT USING "12X, ""T1          T2          Tsat          Lntd          Vu          X          Y""
1710 END IF
1720 ASSIGN @File TO D_files
1730 IF Im=1 AND Jj=0 THEN
1740! READ DATA THROUGH THE DATA ACQUISITION SYSTEM
1750! IF THE INPUT MODE (Im) = 1
1760 BEEP
1770 INPUT "ENTER FLOWMETER READING",Fm
1780 OUTPUT 709:"AR AF60 AL63"
1790 OUTPUT 709:"AS SA"
1800 Etp=0
1810 FOR I=1 TO 20
1820 ENTER 709:Et
1830 Etp=Etp+Et
1840 NEXT I
1850 Etp=Etp/20
1860 OUTPUT 709:"AS SA"
1870 Ptran=0
1880 FOR I=1 TO 50
1890 ENTER 709:Pt
1900 Ptran=Ptran+Pt
1910 NEXT I
1920 Ptran=Ptran/50
1930 OUTPUT 709:"AS SA"
1940 ENTER 709:Bvol
1950 OUTPUT 709:"AS SA"
1960 ENTER 709:Bamp
1970 OUTPUT 709:"AR AF20 AL24"
1980 FOR I=0 TO 4
1990 OUTPUT 709:"AS SA"
2000 ENTER 709:Emf(I)
2010 Emf(I)=ABS(Emf(I))
2020 NEXT I
2030 OUTPUT 713:"T1R2E"
2040 WAIT 2
2050 ENTER 713:T11
2060 OUTPUT 713:"T2R2E"
2070 WAIT 2
2080 ENTER 713:T2
2090 OUTPUT 713:"T1R2E"
2100 WAIT 2
2110 ENTER 713:T12
2120 T1=(T11+T12)*.5
2130 CLEAR 713
2140 ELSE
2150! READ DATA FROM A USER-SPECIFIED FILE IF INPUT MODE (Im) = 2
2160 ENTER @File;Bvol,Bamp,Ptran,Etp,Emf(*),Fm,T1,T2
2170 END IF
2180 Tsat=FNTvsv((Emf(0)+Emf(1))*5)

```

```

2190 T1=FNTvsv(Emf(2))
2200 Grad=FNGrad((T1+T2)*.5)
2210 To=T1+ABS(Etp)/(10*Grad)*1.E+6
2220 IF Jj=0 THEN
2230 Er1=ABS(T1-T1)
2240 PRINTER IS 1
2250 PRINT USING "****T1          = ""'.DD.3D'":T1
2260 PRINT USING "****T1          = ""'.DD.DD'":T1
2270 IF Er1>.5 THEN
2280 BEEP
2290 PRINT "QCT AND TC DIFFER MORE THAN 0.5 C"
2300 BEEP
2310 INPUT "OK TO GO AHEAD (1=Y,0=N)?" ,Ok1
2320 END IF
2330 PRINT USING "****DT (QCT)      = ""'.Z.3D'":T2-T1
2340 PRINT USING "****DT (T-PILE) = ""'.Z.3D'":To-T1
2350 IF Ok1=0 AND Er1>.5 THEN 3600
2360 Er2=ABS((T2-T1)-(To-T1))/(T2-T1)
2370 IF Er2>.05 THEN
2380 BEEP
2390 PRINT "QCT AND T-PILE DIFFER MORE THAN 5%"
2400 BEEP
2410 INPUT "OK TO GO AHEAD (1=Y,0=N)?" ,Ok2
2420 IF Ok2=0 AND Er2>.05 THEN 3600
2430 END IF
2440 PRINTER IS 701
2450 END IF
2460! CALCULATE THE LOG-MEAN-TEMPERATURE DIFFERENCE
2470 IF Itm=1 THEN
2480 Tf=T1
2490 Tl=T2
2500 END IF
2510 IF Itm=2 THEN
2520 Tf=T1
2530 Tl=To
2540 END IF
2550 IF Itm=3 THEN
2560 Tf=(T1+Tl)*.5
2570 Tl=(T2+To)*.5
2580 END IF
2590 Tavg=(Tf+Tl)*.5
2600 Trise=Tl-Tf
2610 Lmtd=Trise/LOG((Tsat-Tf)/(Tsat-Tl))
2620 Cpw=FNCPw(Tavg)
2630 Rhow=FNRRow(Tavg)
2640 Kw=FNKw(Tavg)
2650 Muwa=FNMuw(Tavg)
2660 Pru=FNPrw(Tavg)
2670 Mdt=5.00049E-3+6.9861937E-3*Fm
2680 Md=Mdt*(1.0365-Tf*(1.96644E-3-Tf*5.252E-6))/ .995434
2690 Vf=Md/Rhow
2700 Vu=Vf/(PI*Di^2/4)
2710 Trise=Trise-.004*Vu^2
2720 Q=Md*Cpw*Trise
2730 Qp=Q/(PI*Do*L)
2740 Uo=Qp/Lmtd
2750 Re=Rhow*Vu*Di/Muwa
2760 Fe1=0
2770 Fe2=0
2780 Cf=1
2790 Two=Tsat-5

```

```

2800 Tfilm=Tsats/2+Two/2
2810 Kf=FNKw(Tfilm)
2820 Rhof=FNRhof(Tfilm)
2830 Muf=FNMuw(Tfilm)
2840 Hfgp=FNHfg(Tsat)+.68*FNCpw(Tfilm)*(Tsats-Two)
2850 New=Kf*(Rhof^2+9.799*Hfgp/(Muf*Do*Qp))^-.3333
2860 Ho=.655*New
2870 Twoc=Tsats-Qp/Ho
2880 IF ABS((Twoc-Two)/Twoc)>.001 THEN
2890 Two=Twoc
2900 GOTO 2800
2910 END IF
2920 Cf=1.0
2930 Omega=Re^.8*Pru^-.3333*Cf
2940 Hi=Kw/Di*Ci*Omega
2950 IF Ife=0 THEN 3040
2960 P1=PI*(Di+Do)
2970 P2=PI*(Di+Dr)
2980 A1=(Do-Di)*PI*(Di+Do)*.5
2990 A2=(Dr-Di)*PI*(Di+Dr)*.5
3000 M1=(Hi*P1/(Kcu*A1))^-.5
3010 M2=(Hi*P2/(Kcu*A2))^-.5
3020 Fe1=FNtanh(M1*L1)/(M1*L1)
3030 Fe2=FNtanh(M2*L2)/(M2*L2)
3040 Dt=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
3050 Cfc=(Muwa/FNmuw(Tavg+Dt))^-.14
3060 IF ABS((Cfc-Cf)/Cfc)>.01 THEN
3070 Cf=(Cf+Cfc)*.5
3080 GOTO 2930
3090 END IF
3100 X=Do*New/(Omega*Kw)
3110 Y=New*(1/Uo-Rm)
3120! COMPUTE COEFFICIENTS FOR THE LEAST-SQUARES-FIT STRAIGHT LINE
3130 IF Jp=1 THEN OUTPUT @Filep:X,Y
3140 Sx=Sx+X
3150 Sy=Sy+Y
3160 Sxs=Sxs+X*X
3170 Sxy=Sxy+X*Y
3180! STORE RAW DATA IN A USER-SPECIFIED FILE IF INPUT MODE (Im) = 1
3190 IF Im=1 AND Jj=0 THEN OUTPUT @File:Bvol,Bamp,Ptran,Etp,Emf(*),Fm,T1,T2
3200 IF Jj=0 OR Jp=1 THEN PRINT USING "8X,5(2X,3D,DD),2(2X,D,5D)";Tf,T1,Tsats,Lm
td,Vw,X,Y
3210 BEEP
3220 J=J+1
3230 IF Im=1 AND Jj=0 THEN
3240 INPUT "DO YOU HAVE MORE DATA (1=Y,0=N)?",Go_on
3250 Nrun=J
3260 IF Go_on=1 THEN 1730
3270 ELSE
3280 IF J<Nrun THEN 1730
3290 END IF
3300 S1=(Nrun*Sxy-Sy*Sx)/(Nrun*Sxs-Sx^2)
3310 Ac=(Sy-S1*Sx)/Nrun
3320 Cic=1/S1
3330 Jj=Jj+1
3340 IF Jp=1 THEN Jp=2
3350 IF ABS((Cic-C1)/Cic)>.001 THEN
3360 C1=(Cic+C1)*.5
3370 PRINT USING "10X,.""Intermediate Sieder-Tate coefft = ""Z.4D":C1
3380 GOTO 1600

```

```

3330 ELSE
3400 IF Jp=0 THEN Jp=1
3410 END IF
3420 IF Jp=1 THEN 1600
3430 Ci=(Ci+Cic)*.5
3440 PRINT
3450 PRINT USING "10X, ""Sieder-Tate coefficient          = ""Z.4D":Ci
3460 PRINT
3470 PRINT USING "10X, ""Least-Squares Line: ""
3480 PRINT USING "10X, "" Slope      = ""Z.5DE,":S1
3490 PRINT USING "10X, "" Intercept = ""MZ.5DE,":Ac
3500 PRINT
3510 IF Im=1 THEN
3520 BEEP
3530 PRINT USING "10X, ""NOTE: ""ZZ, "" data runs are stored in file ""8A":J.D_
    files$
3540 ELSE
3550 PRINT USING "10X, ""NOTE: Above analysis was performed for data in file "",
    10A":D_files$
3560 END IF
3570 PRINT USING "16X, ""Plot data are stored in file ""10A":Plots$
3580 ASSIGN @File TO *
3590 ASSIGN @Filep TO *
3600 END
3610 DEF FNRhow(T)
3620 Ro=1006.35724-T*(.774489-T*(2.262459E-2-T*3.03304E-4))
3630 RETURN Ro
3640 FNEND
3650 DEF FNPru(T)
3660 Pru=FNCpu(T)*FNMu(T)/FNKu(T)
3670 RETURN Pru
3680 FNEND
3690 DEF FNMu(T)
3700 A=247.8/(T+133.15)
3710 Mu=2.4E-5*10^A
3720 RETURN Mu
3730 FNEND
3740 DEF FNKu(T)
3750 X=(T+273.15)/273.15
3760 Ku=-.92247+X*(2.8395-X*(1.8007-X*(.52577-.07344*X)))
3770 RETURN Ku
3780 FNEND
3790 DEF FNTvsv(Enf)
3800 COM /Cc/ C(7)
3810 Sum=C(0)
3820 FOR I=1 TO 7
3830 Sum=Sum+C(I)*Enf^I
3840 NEXT I
3850 RETURN Sum
3860 FNEND
3870 DEF FNCpu(T)
3880 Cpu=(4.21120858-T*(2.26826E-3-T*(4.42361E-5+2.71428E-7)))*1000
3890 RETURN Cpu
3900 FNEND
3910 DEF FNTanh(X)
3920 P=EXP(X)
3930 Q=EXP(-X)
3940 Tanh=(P+Q)/(P-Q)
3950 RETURN Tanh
3960 FNEND
3970 DEF FNGrad(T)

```

3980 COM /Cc/ C(?)
3990 Grad=37.9853+.104388*T
4000 RETURN Grad
4010 FNEND
4020 DEF FNFvst(T)
4030 F=466.444+T*(7.09451-T*1.65808E-2)
4040 RETURN F
4050 FNEND
4060 DEF FNFhg(T)
4070 Hfg=2477200-2450*(T-10)
4080 RETURN Hfg
4090 FNEND

PROGRAM DRP

```

1000! FILE NAME: DRP
1010! REVISED: November 18, 1983
1020!
1030 COM /Cc/ C(7)
1040 DIM Emf(10)
1050 DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1060 DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
1070 READ C(*)
1080 Di=.0127      ! Inside diameter of test tube
1090 Do=.01905     ! Outside diameter of test tube
1100 Dr=.015875    ! Outside diameter of the outlet end
1110 Dssp=.1524    ! Inside diameter of stainless steel test section
1120 Ax=PI*Dssp^2/4-PI*Do*L
1130 L=.130175     ! Condensing length
1140 L1=.060325    ! Inlet end "fin length"
1150 L2=.034925    ! Outlet end "fin length"
1160 Kcu=385       ! Thermal conductivity of Copper
1170 Ci=.034      ! Sieder-Tate coefficient
1180 Rm=Do*LOG(Do/Di)/(2*Kcu) ! Wall resistance based on outside area
1190 PRINTER IS 701
1200 CLEAR 709
1210 BEEP
1220 INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Dates$
1230 OUTPUT 709:"TD";Dates$
1240 OUTPUT 709:"TD"
1250 ENTER 709:Dates$
1260 PRINT "      Month, date and time :";Dates$
1270 PRINT
1280 PRINT USING "10X, ""NOTE: Program name : DRP""
1290 BEEP
1300 INPUT "ENTER DISK NUMBER".Dn
1310 PRINT USING "16X, ""Disk number - """,DD";Dn
1320 BEEP
1330 INPUT "ENTER INPUT MODE (1=3054A,2=FILE)".Im
1340 IF Im=1 THEN
1350 BEEP
1360 INPUT "GIVE A NAME FOR THE RAW DATA FILE".D_files$
1370 CREATE BDAT D_files.15
1380 ASSIGN @File TO D_files$
1390 BEEP
1400 INPUT "ENTER GEOMETRY CODE (1=FINNED,0=PLAIN)".Ifg
1410 OUTPUT @File:Ifg
1420 IF Ifg=0 THEN
1430 BEEP
1440 INPUT "WALL TEMPERATURE MEASUREMENT (1=Y,0=N)".Iwt
1450 ELSE
1460 BEEP
1470 INPUT "ENTER FIN PITCH, WIDTH AND HEIGHT".Fp,Fw,Fh
1480 END IF
1490 IF Ifg=0 THEN OUTPUT @File:Iwt
1500 IF Ifg=1 THEN OUTPUT @File:Fp,Fw,Fh
1510 ELSE
1520 BEEP
1530 INPUT "GIVE THE NAME OF THE EXISTING DATA FILE".D_files$
1540 PRINT USING "16X, ""This analysis was performed for data in file """,.10A";D_

```

```

files
1550 BEEP
1560 INPUT "ENTER THE NUMBER OF RUNS STORED".Nrun
1570 ASSIGN @File TO D_files
1580 ENTER @File:Ifg
1590 IF Ifg=0 THEN ENTER @File:Iwt
1600 IF Ifg=1 THEN ENTER @File:Fp,Fw,Fh
1610 END IF
1620 IF Ifg=0 THEN
1630 BEEP
1640 INPUT "WANT TO CREATE A FILE FOR Nr vs F (1=Y,0=N)".Inf
1650 ELSE
1660 Inf=0
1670 END IF
1680 IF Inf=1 THEN
1690 BEEP
1700 INPUT "GIVE A NAME FOR Nr vs F FILE".Nrfs
1710 CREATE BDAT Nrfs,2
1720 ASSIGN @Nrf TO Nrfs
1730 END IF
1740 BEEP
1750 INPUT "ENTER OPTION (1-QCT,2-T-PILE,3-AVE)".Itm
1760 BEEP
1770 INPUT "ENTER OPTION FOR END-FIN EFFECT (1=Y,0=N)".Ife
1780 IF Itm=1 THEN PRINT USING "16X,""This analysis uses QCT readings""
1790 IF Itm=2 THEN PRINT USING "16X,""This analysis uses T-PILE readings""
1800 IF Itm=3 THEN PRINT USING "16X,""This analysis uses average of QCT and T-P
ILE readings""
1810 IF Ife=1 THEN PRINT USING "16X,""This analysis includes end-fin effect""
1820 IF Ife=0 THEN PRINT USING "16X,""This analysis neglects end-fin effect""
1830 PRINT USING "16X,""Sieder-Tate coefficient = """,Z.4D":Ci
1840 BEEP
1850 INPUT "GIVE A NAME FOR PLOT DATA FILE".P_files
1860 CREATE BDAT P_files,5
1870 ASSIGN @Filep TO P_files
1880 IF Iwt=1 THEN
1890 BEEP
1900 INPUT "GIVE A NAME FOR WALL TEMPERATURE FILE".Wtfs
1910 CREATE BDAT Wtfs,5
1920 ASSIGN @Filel TO Wtfs
1930 END IF
1940 BEEP
1950 INPUT "ENTER OUTPUT VERSION (1=SHORT,2=LONG)".Iov
1960! IF Im=1 THEN
1970! OUTPUT @File:Ifg
1980! IF Ifg=0 THEN OUTPUT @File:Iwt
1990! IF Ifg=1 THEN OUTPUT @File:Fp,Fw,Fh
2000! ELSE
2010! ENTER @File:Ifg
2020! IF Ifg=0 THEN ENTER @File:Iwt
2030! IF Ifg=1 THEN ENTER @File:Fp,Fw,Fh
2040! END IF
2050 IF Ifg=0 THEN
2060 PRINT USING "16X,""Tube type : PLAIN""
2070 ELSE
2080 PRINT USING "16X,""Tube type : FINNED""
2090 PRINT USING "16X,""Fin pitch, width, and height (mm): """,DD.D,2X.Z.DD.2X,Z
.DD":Fp,Fw,Fh
2100 END IF
2110 J=0
2120 IF Iov=1 THEN

```

```

2130 PRINT
2140 IF Inf=1 THEN
2150 PRINT USING "10X. ""Data Vu Uo Ho Qp Vv F Nr
      ""
2160 PRINT USING "10X. "" # (m/s) (W/m^2-K) (W/m^2-K) (W/m^2) (m/s) ""
2170 ELSE
2180 PRINT USING "10X. ""Data Vu Uo Ho Qp Vv ""
2190 PRINT USING "10X. "" # (m/s) (W/m^2-K) (W/m^2-K) (W/m^2) (m/s) ""
      ""
2200 END IF
2210 END IF
2220 Sx=0
2230 Sy=0
2240 Sxs=0
2250 Sxy=0
2260 Repeat:
2270 J=J+1
2280 IF Im=1 THEN
2290 BEEP
2300 INPUT "LIKE TO CHECK NG CONCENTRATION (1-Y,0-N)?",Ng
2310 BEEP
2320 INPUT "ENTER FLOWMETER READING".Fm
2330 OUTPUT 709:"AR AF60 AL63 VR5"
2340 OUTPUT 709:"AS SA"
2350 ENTER 709:Etp
2360 OUTPUT 709:"AS SA"
2370 Vtran=0
2380 FOR I=1 TO 50
2390 ENTER 709:Vt
2400 Vtran=Vtran+Vt
2410 NEXT I
2420 Vtran=Vtran/50
2430 OUTPUT 709:"AS SA"
2440 ENTER 709:Bvol
2450 OUTPUT 709:"AS SA"
2460 ENTER 709:Bamp
2470 IF Iwt=0 THEN OUTPUT 709:"AR AF20 AL24 VR1"
2480 IF Iwt=1 THEN OUTPUT 709:"AR AF20 AL30 VR1"
2490 IF Iwt=0 THEN Nn=4
2500 IF Iwt=1 THEN Nn=10
2510 FOR I=0 TO Nn
2520 OUTPUT 709:"AS SA"
2530 IF I>4 THEN
2540 Se=0
2550 FOR K=0 TO 10
2560 ENTER 709:E
2570 Se=Se+E
2580 NEXT K
2590 Emf(I)=ABS(Se/10)
2600 ELSE
2610 ENTER 709:E
2620 Emf(I)=ABS(E)
2630 END IF
2640 NEXT I
2650 OUTPUT 713:"T1R2E"
2660 WAIT 2
2670 ENTER 713:T11
2680 OUTPUT 713:"T2R2E"
2690 WAIT 2
2700 ENTER 713:T2

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2710 OUTPUT 713:"TIR2E"
2720 WAIT 2
2730 ENTER 713:T12
2740 T1=(T11+T12)*.5
2750 IF Ng=0 THEN 2800
2760 BEEP
2770 INPUT "ENTER MANOMETER READING (HL,HR,HRW)".H1,HR,HRW
2780 Phg=H1+HR
2790 Pwater=HR-HRW
2800 ELSE
2810 IF Ifg=1 OR Iwt=0 THEN
2820 ENTER @File:Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),Fm,T1,T
2.Phg,Pwater
2830 END IF
2840 IF Ifg=0 AND Iwt=1 THEN ENTER @File:Bvol,Bamp,Vtran,Etp,Emf(*),Fm,T1,T2,Ph
g,Pwater
2850 IF J=1 OR J=10 OR J=20 OR J=Nrun THEN
2860 Ng=1
2870 ELSE
2880 Ng=0
2890 END IF
2900 END IF
2910 Tsteam=FNTvsv((Emf(0)+Emf(1))*5) ! COMPUTE STEAM TEMPERATURE
2920 Troom=FNTvsv(Emf(3))
2930 IF Iwt=1 THEN
2940 Tum=0.
2950 FOR I=0 TO 5
2960 Tw(I)=FNTvsv(Emf(I+5))
2970 Tum=Tum+Tw(I)
2980 NEXT I
2990 Tum=Tum/6
3000 END IF
3010 Tcon=FNTvsv(Emf(4))
3020 Psat=FNpvst(Tsteam)
3030 Rohg=13529-122*(Troom-26.85)/50
3040 Rowater=FNrhov(Troom)
3050 Ptest=(Phg-Rohg-Pwater-Rowater)*9.799/1000
3060 Pmm=Ptest/133.322
3070 Pkm=Ptest*1.E-3
3080 Pks=Psat*1.E-3
3090 Pkt=FNpvsv(Vtran)*1.E-3
3100 Tsat=FNTvsp(Ptest)
3110 Vst=FNvst(Tsteam)
3120 Ppng=(Ptest-Psat)/Ptest
3130 Ppst=1-Ppng
3140 Mfng=1/(1+18.015/28.97*Psat/(Ptest-Psat))
3150 Vfng=Mfng/(1.608-.608*Mfng)
3160 Mfng=Mfng*100
3170 Vfng=Vfng*100
3180 BEEP
3190 IF Iov=2 THEN
3200 PRINT
3210 PRINT USING "10X, ""Data set number          = ""'.DD";J
3220 PRINT
3230 END IF
3240 IF Iov=2 AND Ng=1 THEN
3250 PRINT USING "10X, ""          P          Psat      Ptran      Tmeas      Tsat          N
G %""
3260 PRINT USING "10X, "" (mm)      (kPa)      (kPa)      (kPa)      (C)      (C)      Molal
Mass""
3270 PRINT USING "10X,5(3D.DD,2X).2(3D.DD,2X).2(M3D.D,2X)":Pmm,Pkm,Pks,Pkt,Tste

```

```

am.Tsat,Vfng,Mfng
3280 PRINT
3290 END IF
3300 IF Mfng>.5 THEN
3310 BEEP
3320 PRINT
3330 IF Im=1 THEN
3340 BEEP
3350 PRINT
3360 PRINT USING "10X.""Energize the vacuum system ""
3370 BEEP
3380 INPUT "OK TO ACCEPT THIS RUN (1-Y,0-N)?",Ok
3390 IF Ok=0 THEN
3400 BEEP
3410 DISP "NOTE: THIS DATA SET WILL BE DISCARDED!! "
3420 WAIT 5
3430 GOTO 2280
3440 END IF
3450 END IF
3460 END IF
3470 IF Im=1 THEN
3480 IF Ifg=1 OR Iwt=0 THEN
3490 OUTPUT @File:Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),Fm,T1,
T2,Phg,Pwater
3500 END IF
3510 IF Ifg=0 AND Iwt=1 THEN OUTPUT @File:Bvol,Bamp,Vtran,Etp,Emf(*),Fm,T1,T2,P
hg,Pwater
3520 END IF
3530 IF Ifg=0 AND Iwt=1 THEN OUTPUT @File!;Tu(*)
3540! ANALYSIS BEGINS
3550 T1=FNTvsv(Emf(2))
3560 Grad=FNGrad((T1+T2)*.5)
3570 To=T1+ABS(Etp)/(10*Grad)*1.E+6
3580 Er1=ABS(T1-T1)
3590 PRINTER IS 1
3600 PRINT USING ""T1 (QCT) = ""'.DD.3D":T1
3610 PRINT USING ""T1 (TC) = ""'.DD.3D":T1
3620 IF Er1>.5 THEN
3630 BEEP
3640 PRINT "QCT AND TC DIFFER BY MORE THAN 0.5 C"
3650 BEEP
3660 INPUT "OK TO GO AHEAD (1-Y,0-N)?",Ok1
3670 END IF
3680 PRINT USING ""DT (QCT) = ""'.Z.3D":T2-T1
3690 PRINT USING ""DT (T-PILE) = ""'.Z.3D":To-T1
3700 IF Ok1=0 AND Er1>.5 THEN 5100
3710 Er2=ABS((T2-T1)-(To-T1))/(T2-T1)
3720 IF Er2>.05 THEN
3730 BEEP
3740 PRINT "QCT AND T-PILE DIFFER BY MORE THAN 5%"
3750 BEEP
3760 INPUT "OK TO GO AHEAD (1-Y,0-N)?",Ok2
3770 IF Ok2=0 AND Er2>.05 THEN 5100
3780 END IF
3790 PRINTER IS 701
3800 IF Itm=1 THEN
3810 T1i=T1
3820 T2o=T2
3830 END IF
3840 IF Itm=2 THEN
3850 T1i=T1

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3860 T2o=To
3870 END IF
3880 IF Itm=3 THEN
3890 T1i=(T1+T1)*.5
3900 T2o=(T2+To)*.5
3910 END IF
3920 Tavg=(T1i+T2o)*.5
3930 Cpw=FNCpw(Tavg)
3940 Rhow=FNRhow(Tavg)
3950 Md=5.00049E-3+6.9861937E-3*Fn
3960 Md=Md*(1.0365-1.96644E-3*Tavg+5.252E-6*Tavg^2)/.995434
3970 Mf=Md/Rhow
3980 Vu=Mf/(PI*Di^2/4)
3990 T2o=T2o-(.0138+.001*Vu^2)
4000 Q=Md*Cpw*(T2o-T1i)
4010 Qp=Q/(PI*Do*L)
4020 Ku=FNKu(Tavg)
4030 Mum=FNHmum(Tavg)
4040 Rei=Rhow*Vu*Di/Mum
4050 Pru=FNPru(Tavg)
4060 Fe1=0.
4070 Fe2=0.
4080 Cf=1.
4090 Hi=Ku*C1/Di*Rei^.8*Pru^.3333*Cf
4100 Dt=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
4110 Cfc=(Mum/FNMum(Tavg+Dt))^.14
4120 IF ABS((Cfc-Cf)/Cfc)>.01 THEN
4130 Cf=(Cf+Cfc)*.5
4140 GOTO 4090
4150 END IF
4160 IF Ife=0 THEN GOTO 4250
4170 P1=PI*(Di+Do)
4180 A1=(Do-Di)*PI*(Di+Do)*.5
4190 M1=(Hi*P1/(Kcu*A1))^.5
4200 P2=PI*(Di+Dr)
4210 A2=(Dr-Di)*PI*(Di+Dr)*.5
4220 M2=(Hi*P2/(Kcu*A2))^.5
4230 Fe1=FNtanh(M1*L1)/(M1*L1)
4240 Fe2=FNtanh(M2*L2)/(M2*L2)
4250 Lmtd=(T2o-T1i)/LOG((Tsteam-T1i)/(Tsteam-T2o))
4260 Uo=Q/(Lmtd*PI*Do*L)
4270 Ho=1/(1/Uo+Do*L/(Di*(L+L1*Fe1+L2*Fe2)*Hi)-Rm)
4280 Dtc=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
4290 IF ABS((Dtc-Dt)/Dtc)>.01 THEN 4090
4300 Hfg=FNHfg(Tsteam)
4310 Two=Tsteam-Qp/Ho
4320 Tfilm=Tsteam/3+2*Two/3
4330 Kf=FNKu(Tfilm)
4340 Rhof=FNRhow(Tfilm)
4350 Muf=FNHmum(Tfilm)
4360 Hpq=.651*Kf*(Rhof^2+9.81*Hfg/(Muf*Do*Qp))^.3333
4370 Y=Hpq*Qp^.3333
4380 X=Qp
4390 Sx=Sx+X
4400 Sy=Sy+Y
4410 Sxs=Sxs+X^2
4420 Sxy=Sxy+X*Y
4430 OUTPUT @Filep:Qp,Ho
4440 Q1=500 ! TO BE MODIFIED
4450 Qloss=Q1/(100-25)*(Tsteam-Troom) ! TO BE MODIFIED
4460 Hfc=FNHF(Tcon)

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4470 Hf=FNHf(Tsteam)
4480 Mdv=0
4490! Bp=(Bvol*100)^2/5.76 ! BOILER POWER IN Watts
4500 Bp=(Bvol*100)^2/5.76
4510 Mdvc=((Bp-Qloss)-Mdv*(Hf-Hfc))/Hfg
4520 IF ABS((Mdv-Mdvc)/Mdvc)>.01 THEN
4530 Mdv=(Mdv+Mdvc)*.5
4540 GOTO 4510
4550 END IF
4560 Mdv=(Mdv+Mdvc)*.5
4570 Vg=FNVgst(Tsteam)
4580 Vv=Mdv/Vg/Ax
4590 IF Inf=1 THEN
4600 F=(9.799*Do*Muf+Hfg)/(Vv^2*Kf*(Tsteam-Two))
4610 Nu=Ho*Do/Kf
4620 Ret=Vv*Rhof*Do/Muf
4630 Nr=Nu/Ret^.5
4640 END IF
4650 IF Inf=1 THEN OUTPUT @Nrf:F,Nr
4660 IF Iov=2 THEN
4670 PRINT USING "10X,"" T (Inlet) Delta-T""
4680 PRINT USING "10X,"" QCT TC QCT T-PILE""
4690 PRINT USING "10X,2(DD.DD.2X),2(Z.3D.2X)";T1,T1,T2-T1,To-T1
4700 PRINT USING "10X,"" Vw Rei Hi Uo Ho q
Vv""
4710 PRINT USING "10X,Z.DD,1X,5(MZ.3DE,1X),MZ.DD";Vw,Rei,Hi,Uo,Ho,Qp,Vv
4720 END IF
4730 IF Iov=1 THEN
4740 IF Inf=1 THEN
4750 PRINT USING "11X.DD.2X,Z.DD.2X,2(5D.D.2X),Z.3DE,1X,Z.DD,2(1X.3D.DD)";J,Vw,
Uo,Ho,Qp,Vv,F,Nr
4760 ELSE
4770 PRINT USING "11X.DD.2X,Z.DD.2X,2(MD.4DE.2X),Z.3DE.3X,Z.DD";J,Vw,Uo,Ho,Qp,V
v
4780 END IF
4790 END IF
4800 IF Im=1 THEN
4810 BEEP
4820 INPUT "WILL THERE BE ANOTHER RUN (1=Y,0=N)?",Go_on
4830 Nrun=J
4840 IF Go_on=1 THEN Repeat
4850 ELSE
4860 IF J<Nrun THEN Repeat
4870 END IF
4880 IF Ifg=0 THEN
4890 PRINT
4900 S1=(Nrun*Sxy-Sy*Sx)/(Nrun*Sxs-Sx^2)
4910 Ac=(Sy-S1*Sx)/Nrun
4920 PRINT USING "10X,""Least-Squares Line for Hnu vs q curve:""
4930 PRINT USING "10X,"" Slope = "",MD.4DE";S1
4940 PRINT USING "10X,"" Intercept = "",MD.4DE";Ac
4950 END IF
4960 IF Im=1 THEN
4970 BEEP
4980 PRINT
4990 PRINT USING "10X,""NOTE: "",ZZ."" data runs were stored in file "",10A";J.
D files
5000 END IF
5010 BEEP
5020 PRINT
5030 PRINT USING "10X,""NOTE: "",ZZ."" X-Y pairs were stored in plot data file

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"" ,10A":J.P_files
5040 IF Inf=1 THEN
5050 PRINT USING "16X,ZZ,."" pairs of Nr-F are stored in file "" ,14A":J.Nrfs
5060 END IF
5070 ASSIGN @File TO *
5080 ASSIGN @File1 TO *
5090 ASSIGN @Filep TO *
5100 END
5110 DEF FNPvst(Tsteam)
5120 DIM K(8)
5130 DATA -7.691234564,-26.08023696,-168.1706546,64.23285504,-118.9646225
5140 DATA 4.16711732,20.9750676,1.E9.6
5150 READ K(*)
5160 T=(Tsteam+273.15)/647.3
5170 Sum=0
5180 FOR N=0 TO 4
5190 Sum=Sum+K(N)*(1-T)^(N+1)
5200 NEXT N
5210 Br=Sum/(T*(1+K(5)*(1-T)+K(6)*(1-T)^2))-(1-T)/(K(7)*(1-T)^2+K(8))
5220 Pr=EXP(Br)
5230 P=22120000*Pr
5240 RETURN P
5250 FNEND
5260 DEF FNHfg(T)
5270 Hfg=2477200-2450*(T-10)
5280 RETURN Hfg
5290 FNEND
5300 DEF FNMu(T)
5310 A=247.8/(T+133.15)
5320 Mu=2.4E-5*10^A
5330 RETURN Mu
5340 FNEND
5350 DEF FNVvst(Tt)
5360 P=FNPvst(Tt)
5370 T=Tt+273.15
5380 X=1500/T
5390 F1=1/(1+T*1.E-4)
5400 F2=(1-EXP(-X))^2.5*EXP(X)/X^.5
5410 B=.0015*F1-.000942*F2-.0004882*X
5420 K=2*P/(461.52*T)
5430 V=(1+(1+2*B*K)^.5)/K
5440 RETURN V
5450 FNEND
5460 DEF FNCpu(T)
5470 Cpu=4.21120858-T*(2.26826E-3-T*(4.42361E-5+2.71428E-7*T))
5480 RETURN Cpu*1000
5490 FNEND
5500 DEF FNRhou(T)
5510 Ro=999.52946+T*(.01269-T*(5.482513E-3-T*1.234147E-5))
5520 RETURN Ro
5530 FNEND
5540 DEF FNPru(T)
5550! Pru=10*(1.09976605-T*(1.3749326E-2-T*(3.968875E-5-3.45026E-7*T)))
5560 Pru=FNCpu(T)*FNMu(T)/FNKu(T)
5570 RETURN Pru
5580 FNEND
5590 DEF FNKu(T)
5600! Ku=.5625894+T*(2.2964546E-3-T*(1.509766E-5-4.0581652E-8*T))
5610 X=(T+273.15)/273.15
5620 Ku=-.92247+X*(2.8395-X*(1.8007-X*(.52577-.07344*X)))
5630 RETURN Ku

```

```

5640 FNEND
5650 DEF FNTanh(X)
5660 P=EXP(X)
5670 Q=EXP(-X)
5680 Tanh=(P+Q)/(P-Q)
5690 RETURN Tanh
5700 FNEND
5710 DEF FNTvsv(V)
5720 COM /Cc/ C(7)
5730 Sum=C(0)
5740 FOR I=1 TO 7
5750 Sum=Sum+C(I)*V^I
5760 NEXT I
5770! T=V*(.02635206856-V*(9.7351313E-7-V*6.576805E-11))
5780 RETURN Sum
5790 FNEND
5800 DEF FNHF(T)
5810 Hf=T*(4.203849-T*(5.88132E-4-T*4.55160317E-6))
5820 RETURN Hf*1000
5830 FNEND
5840 DEF FNGrad(T)
5850 Grad=37.9853+.104388*T
5860 RETURN Grad
5870 FNEND
5880 DEF FNTvsp(P)
5890 Tu=110
5900 Tl=10
5910 Ta=(Tu+Tl)*.5
5920 Pc=FNpvst(Ta)
5930 IF ABS((P-Pc)/P)>.001 THEN
5940 IF Pc<P THEN Tl=Ta
5950 IF Pc>P THEN Tu=Ta
5960 GOTO 5910
5970 END IF
5980 RETURN Ta
5990 FNEND
6000 DEF FNPvsv(V)
6010 P=8133.5133+2.236051E+4*V
6020 RETURN P
6030 FNEND

```

PROGRAM TCAL

```

100 : FILE NAME: TCAL
110 : REVISED: December 11, 1983
120 :
130 COM /C=/ C(7)
140 DIM Emf(10),T(10),D(10)
150 DATA 0.10086091,25727.94369,-767345.8295,78025595.81
160 DATA -9247486589,6.97688E11,-2.66192E13,3.94078E14
170 READ C(*)
180 CLEAR 709
190 BEEP
200 INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",BS
210 J=0
220 OUTPUT 709:"TD":BS
230 OUTPUT 709:"TD"
240 ENTER 709:AS
250 PRINT USING "10X.";"Month. date and time = """,14A";AS
260 BEEP
270 INPUT "ENTER INPUT MODE (1=3054A, 2=FILE)",Im
280 IF Im=1 THEN
290 BEEP
300 INPUT "GIVE A NAME FOR DATA FILE",D_files
310 CREATE BDAT D_files.5
320 ELSE
330 BEEP
340 INPUT "GIVE NAME OF EXISTING FILE",D_files
350 BEEP
360 INPUT "ENTER NUMBER OF DATA RUNS STORED",Nrun
370 END IF
380 BEEP
390 INPUT "GIVE A NAME FOR PLOT FILE",P_files
400 CREATE BDAT P_files.5
410 ASSIGN @Plot TO P_files
420 ASSIGN @File TO D_files
430 IF Im=1 THEN
440 BEEP
450 INPUT "ENTER BATH TEMPERATURE",T_bath
460 OUTPUT 709;"AR AF20 AL30"
470 FOR I=0 TO 10
480 OUTPUT 709;"AS SA"
490 ENTER 709:Emf(I)
500 NEXT I
510 OUTPUT 713:"T1R2E"
520 WAIT 2
530 ENTER 713:T1
540 OUTPUT 713:"T2R2E"
550 WAIT 2
560 ENTER 713:T2
570 OUTPUT @File:T_bath.Emf(*),T1,T2
580 ELSE
590 ENTER @File:T_bath.Emf(*),T1,T2
600 END IF
610 J=J+1
620 Dwa=0
630 FOR I=0 TO 10
640 T(I)=FNTvsu(ABS(Emf(I)))
650 D(I)=T_bath-T(I)
660 IF I>4 THEN Dwa=Dwa+D(I)
670 NEXT I
680 Dwa=Dwa/6

```

```

690 Dsa=(D(0)+D(1))*5
700 OUTPUT @Plot;T_bath.Dsa.Dwa
710 PRINT
720 PRINT USING "10X, ""Data set number = "",DD";J
730 PRINT USING "10X, ""Bath T (C)    QCT-1 (C)    QCT-2 (C)""";
740 PRINT USING "10X,3(3D.3D.7X)";T_bath.T1,T2
750 PRINT USING "10X, ""Thermocouple readings (Deg C):""";
760 PRINT USING "10X,6(3D.0D.3X),16X";T(*)
770 PRINT USING "10X, ""Discrepancies (Deg C):""";
780 PRINT USING "11X,6(MZ.DD.4X),15X";D(*)
790 BEEP
800 IF Im=1 THEN
810 INPUT "ARE YOU TAKING MORE DATA (1=Y,0=N)?".Go_on
820 IF Go_on=1 THEN 430
830 ELSE
840 IF J<Nrun THEN 430
850 END IF
860 PRINT
870 IF Im=1 THEN
880 PRINT USING "10X, ""NOTE: "",DD, "" data sets are stored in file "",14A";J.D
   files
890 ELSE
900 PRINT USING "10X, ""NOTE: Above analysis was performed from file "",14A";D_
   files
910 END IF
920 PRINT USING "16X, ""Plot data are stored in file "",10A";P_files
930 ASSIGN @File TO *
940 ASSIGN @Plot TO *.
950 END
960 DEF FNTvsv(Emf)
970 COM /Cc/ C(7)
980 Sum=C(0)
990 FOR I=1 TO 7
1000 Sum=Sum+C(I)*Emf^I
1010 NEXT I
1020 RETURN Sum
1030 FNEND

```

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