CONDENSATION OF MIXTURES GIVING TWO LIQUID PHASES ON A VERTICAL SURFACE

By

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PREFACE

Condensation of mixed vapors resulting in two immiscible liquid phases was studied. The condensation surface was a 26 inch long, SS 304 vertical flat plate. The mixtures studied were toluene-water and R-113-water. Data obtained include visual observations and local heat transfer coefficients.

Three condensate flow models were proposed. The pseudo-homogeneous model was used to correlate the mixture data. Using the condensate Prandtl number the mixture data were correlated with single component data and a method to predict the condensing heat transfer coefficients was proposed.

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NOMENCLATURE

Roman

A	condensation surface area, ft^2 (m^2)
C	number of components
C_p	specific heat, Btu/lb•°F (J/kg•°C)
D	diameter of the condensation surface, ft (m)
D_{eq}	equivalent diameter, in or ft (m)
F	degrees of freedom
g	gravitational acceleration, ft/hr^2 (m/hr^2)
h	condensing heat transfer coefficient, $Btu/hr \cdot ft^2 \cdot °F$ ($w/m^2 \cdot °C$)
h_o	h for the organic phase, calculated assuming that the organic phase alone is condensing on the entire surface, $Btu/hr \cdot ft^2 \cdot °F$ ($w/m^2 \cdot °C$)
h_w	h for the aqueous phase, calculated assuming that the aqueous phase alone is condensing on the entire surface, $Btu/hr \cdot ft^2 \cdot °F$ ($w/m^2 \cdot °C$)
k	thermal conductivity, $Btu/hr \cdot ft^2 \cdot (°F/ft)$, $w/m^2 \cdot (°C/m)$
L	length of the condensing surface, ft (m)
M.W.	molecular weight
Nu	Nusselt number = $\frac{hD}{k}$
N_{co_x}	local condensation number = $h_x \left(\frac{k_l^3 \rho_l^2 g}{\mu_l^2}\right)^{-1/3}$
P	number of phases
Pr	Prandtl number = $\frac{c_p \mu}{k}$

Q	condensation heat load, Btu/hr (w)
Re	Reynolds number = $\frac{4\Gamma}{\mu_l}$
v	condensate volumetric flow rate, ft^3/hr (m^3/hr)
w	condensate mass flow rate, lb_m/hr (kg/hr)

Greek

γ	spreading coefficient, dynes/cm
Γ	condensate loading, lb/hr•ft (kg/hr•m)
Δ	differential quantity
ΔT_f	temperature difference across the condensate layer, between the wall and the vapor liquid interface, °F (°C)
ΔX	incremental distance, in or ft (m)
λ	latent heat of condensation, Btu/lb (J/kg)
μ	viscosity, lb/hr•ft (kg/hr•m)
ρ	density, lb/ft^3 (kg/m^3)
σ	interfacial tension, dynes/cm

Subscripts

A	property of substance A
AT1	based on Akers-Turner Equation 1
AT2	based on Akers-Turner Equation 2
B	property of substance B
BK	based on Boyko-Kruzhilin equation
C	cumulative value
l	pure liquid property in case of single liquid component; averaged liquid property in case of a mixture
Nu	based on Nusselt equation

0 organic phase property

v pure vapor property in case of single vapor component; averaged vapor property in case of a mixture.

w aqueous phase property

x local value

CHAPTER I

INTRODUCTION

Condensation

During the condensation of a single component, two types of condensing mechanisms are commonly observed. These are dropwise condensation and filmwise condensation. In dropwise condensation, the condensate forms drops on the surface and drains in the form of drops. In filmwise condensation the condensate forms a film on the surface and drains as a continuous film.

The condensing heat transfer coefficient (henceforth referred to as the condensing coefficient) may be defined as the ratio of the heat flux divided by the temperature driving force between the vapor-liquid interface and the condensing surface.

The dropwise condensation phenomenon is still not well understood. It has been a subject of interest for a number of years because of the high condensing coefficients observed. Several theories have been proposed to explain this phenomenon and among others, Bernhardt (6) has done a comprehensive literature survey on this subject.

The mechanism of filmwise condensation is quite well understood. In 1916 Nusselt published the first sound theoretical development to calculate the heat transfer coefficient for the filmwise condensation of a single component. He made several assumptions, such as laminar flow of the condensate film, no vapor shear, no liquid subcooling, etc., and obtained the following equations for filmwise condensation on two important surface geometries. For a single horizontal tube with condensation on the outside surface, the condensing coefficient h is given by:

$$h = 0.729 \left[\frac{k_l^3 \ \rho_l^2 \ g \ \lambda}{\mu_l \ \Delta T_f \ D}\right]^{1/4} \tag{1.1}$$

and for a vertical tube with condensation on the outside surface,

$$h = 0.743 \left[\frac{k_l^3 \ \rho_l^2 \ g \ \lambda}{\mu_l \ \Delta T_f \ L}\right]^{1/4} \tag{1.2}$$

The assumptions behind the Nusselt theory are given in Appendix A. The original treatment of Nusselt is analyzed by Kern (26) and Jakob (21) in great detail.

For cases where one or more of Nusselt's assumptions break down, numerous studies have been published. A few notable ones are the effect of turbulent condensate film studied by Colburn (13), the effect of vapor shear studied by Boyko and Kruzhilin (10) and Rohsenow (39), and the effect of condensate subcooling analyzed by Rohsenow (38) and Bromley (12).

In this work the condensation of immiscible mixtures is studied. Condensation of immiscible mixtures is encountered in a variety of process and related industries. The mixtures usually contain water as one of the components. The organic substance may vary from crude oil to turpentine to a styrene-butadiene mixture. The mechanism of condensation from a mixed vapor into two or more liquid phases is not well understood.

When a single substance condenses on a solid surface, the three forces that govern the condensing pattern are gravity, vapor shear and the interfacial tension between the liquid and the solid surface. When a mixture of vapors condenses to form multiple immiscible liquid phases, the interfacial tension between the liquid phases is expected to be an important force. This would dictate how the liquid phases may compete for the solid surface and give rise to different condensing patterns. The next chapter contains a detailed description of the several condensing patterns that have been predicted and observed.

Thermodynamics

When a mixture of immiscible liquids is heated, each liquid exerts its own vapor pressure. When the sum of the vapor pressures equals the total pressure on the system, the liquid temperature is the bubble point of the mixture at the prevailing total pressure. The resulting vapor mixture is eutectic in composition at the prevailing pressure. In this vapor mixture, the mole fractions of the two substances are directly proportional to their vapor pressures at the bubble point temperature. A eutectic diagram for a mixture of two immiscible liquids is shown in Figure 1.

Gibbs' phase rule can be stated as:

$$F + P = C + 2 \qquad (1.3)$$

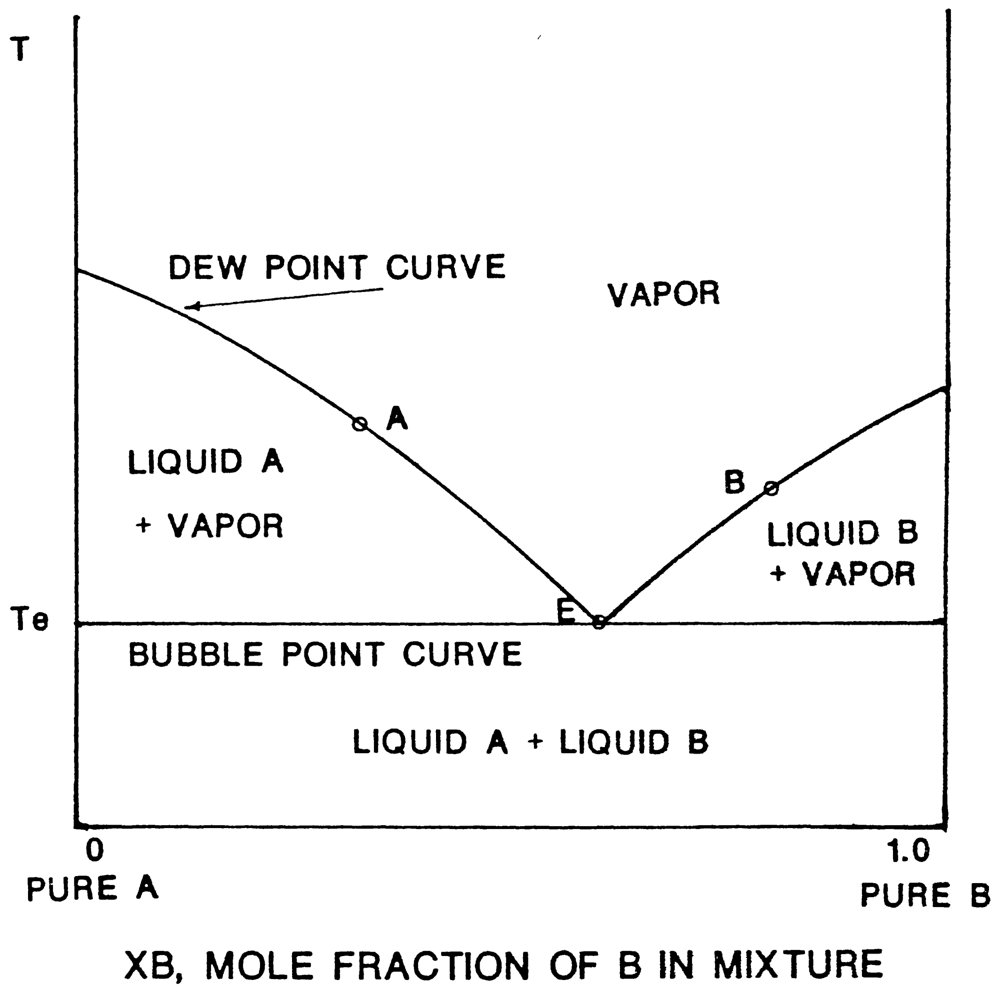

Figure 1. Eutectic Diagram

While boiling two immiscible pure liquids, (C=2) there are two liquid phases and one vapor phase present (P=3). This leaves only one degree of freedom (F=1). This could be either pressure or temperature, the selection of one fixing the other. Hence boiling two liquids together will, in theory, always result in a vapor phase of eutectic composition. If a vapor mixture with non-eutectic composition is needed, the two liquids must be boiled separately and the vapors mixed.

If the vapor composition is eutectic, condensation at the same pressure as boiling will result in condensate of eutectic composition. This is represented by point E in Figure 1. However, if the vapor is richer in one component, that component will condense first selectively, until the vapor phase attains the eutectic composition. This is indicated by the transformation from point A or B to point E in Figure 1. In this case, the condensate in equilibrium with a non-eutectic vapor mixture will not be eutectic in composition. This work will be restricted to condensation of immiscible mixtures of eutectic composition. Partially and completely soluble liquid mixtures are not studied.

A detailed survey of published literature on the subject of immiscible mixture condensation is included in Chapter II. As will be seen later, several researchers have obtained data on condensing coefficients and the condensing patterns. Several empirical equations have been proposed to predict the condensing coefficients. Most of the equations are confined to particular systems and geometries. A wide variety of surfaces have been used. These include gold-plated copper, Teflon®, brass and copper. Many times the surface geometry used (such as 1 in. diameter gold-plated surface) is impractical from the point of industrial applications.

In this work, a vertical stainless steel condensing surface is used to study the condensation of the toluene-water eutectic mixture and the R-113-water eutectic mixture. The objectives of this work were to:

1. Design and construct the necessary apparatus.

2. Test the system using single component systems.

3. Obtain reliable local data for condensation of eutectic toluene-water and R-113-water mixtures. These measurements include local heat fluxes, surface temperatures and the condensate flow patterns.

4. Test the prediction methods proposed in the literature.

5. Identify the best available method (if any) or propose a new method for the prediction of the condensing coefficients.

6. Begin to make progress in characterizing the condensate flow patterns on practical condensing surfaces.

CHAPTER II

LITERATURE REVIEW

Introduction

The existing literature on the subject of immiscible mixture condensation can be classified based on the geometry of the apparatus used in the investigation. A vertical or horizontal tube was the most commonly used geometry. The condensate flow mechanisms described by Hazelton and Baker (20) are referred to in many studies and hence, these are summarized first. The equations derived or proposed by various researchers are summarized in Table 1. All the equations using dimensional correlations are to be used with the English system of units.

Hazelton and Baker have postulated six types of condensate flow patterns:

> Flow Type 1 (film-drop) - The organic liquid completely wets the condensing surface, forming a continuous film which displaces water from any point at which it may be originally in contact with the surface. The organic liquid condenses as a film and flows from the surface as a film. The water forms drops on the surface of the organic film and flows from the surface as a series of drops.
>
> Flow Type 2 - The converse of flow type 1, water forming the continuous film.
>
> Flow Type 3 (channeling) - Some areas of the condenser surface are wet by the organic liquid; the remainder is wet by water. Both liquids form films over the area they wet and flow from these areas as films. Where there is an organic film, a portion of condensing water forms drops on its surface and flows from it in discrete

TABLE I

SUMMARY OF PREVIOUS INVESTIGATIONS

Investigator	Correlation Proposed	
Hazelton and Baker (20)	$h = 79 \left(\frac{w_o \lambda_o + w_w \lambda_w}{w_o L}\right)^{1/4}$ for vertical tubes	(2.1)
	$h = 61 \left(\frac{w_o \lambda_o + w_w \lambda_w}{w_o D}\right)^{1/4}$ for horizontal tubes	(2.2)
Edwards et al. (17)	$h = 0.78(1.22)^{\pm 1} \left(\frac{4\Gamma}{\mu_o}\right)^{-0.102 \pm 0.047} \left(\frac{k_o^3 \rho_o^2 g}{\mu_o^2}\right)^{1/3}$	(2.3)
Tobias and Stoppel (44)	$h = \frac{h_{HB}}{1 - \frac{1}{545}\left[\left(\frac{\Delta\gamma^3 \lvert\Delta\rho\rvert}{\mu_o^4 g}\right) \left(\frac{w_o \rho_w k_w}{w_w \rho_o k_o}\right)^{1/2}\right]^{0.21}}$ h_{HB} = h from Hazelton and Baker equation	(2.4)

α

TABLE I (CONTINUED)

Investigator	Correlation Proposed	
Krishnaiah and Satyanarayan (28)	$h = 2.55 \left(\frac{h_o v_o + h_w v_w}{v_o + v_w}\right)^{0.85}$	(2.5)
	$h = 1.91 \left(\frac{w_o \lambda_o + w_w \lambda_o}{W_o L}\right)^{0.815}$ for vertical surface	(2.6)
Ponter, et al. (36)	$h = a \, \Delta T_f^{\,b}$ a and b vary with the organic component	(2.7)
Kirkbride (27)	$h = \left(\frac{Q_o h_o + Q_w h_w}{Q_o + Q_w}\right)$	(2.8)
Baker and Mueller (3)	$h \left(\frac{\mu_o^2}{k_1^3 \rho_1^2 g}\right)^{1/3} = 1.28 \left(\frac{Cp_1 \mu_o \rho_1^{0.7}}{k_1 \lambda_1}\right)^{2.38} \left(\frac{Q_o}{Q_w + Q_o}\right)^{-3.28}$	(2.9)

TABLE I (CONTINUED)

Investigator	Correlation Proposed	
Baker and Tsao (4)	$\frac{h}{1 - \frac{0.0167}{D}} = \frac{500}{1 - 0.85\ (\frac{V_w}{V_o + V_w})} + 80$	(2.10)
	$h = \frac{366\ (\frac{1}{D})^{1/4}\ (1 - \frac{0.0284}{D})}{1 - 0.85\ (\frac{V_w}{V_o + V_w})} + \frac{1.67}{D}$	(2.11)
Stepanek and Standart (42)	$h = 0.725\ (\frac{\lambda^* \ k_o^3 \ \rho_o^2 \ g}{\mu_o \ \Delta T_f \ D})^{1/4} \ C_1 \ (1 + C_2 \ \Delta T_f)$ where $\lambda^* = \frac{w_w \ \lambda_w + w_o \ \lambda_o}{w_o}$	(2.12)

TABLE I (CONTINUED)

Investigator	Correlation Proposed	
	$C_1 = [1 - 4.38 (\frac{W_w}{W_o})^{0.033} (\frac{\rho_o}{\rho_w}) (\frac{\Delta\sigma}{\sigma_w})^{3.2}]^{1/4}$	
	$C_2 = 0.0584 (\frac{w_w}{w_o}) (\frac{k_o}{k_w})^{0.5} (\frac{\rho_w}{\rho_o})^{1.4} (\frac{\Delta\sigma}{\sigma_w})^{1.6}$	
Sykes and Marchello (43)	$h = h_o (1 - 0.8R) \Delta T_f^{0.67R}$	(2.13)
	where	
	$R = (\Delta\rho \frac{\rho_w}{\rho_o})^{1/2}$	
	$h = h_o (C_1 + \frac{1}{C_2 e^{(0.035 \Delta T_f)}})^{-1}$	(2.14)
	where	
	$C_1 = [7.6 - 1.8 (Pr_o - Pr_w)]$	
	$C_2 = \frac{17.3 \times 10^{-10} Pr_o (1 + \frac{w_o \lambda_o}{w_w \lambda_w})}{[(\frac{\mu_o}{\rho_o g D \sigma_o})^{1/2} (\frac{\Delta\sigma}{\sigma_o}) (\frac{\mu_o}{\mu_w}) (\frac{M.W._w}{M.W._o})]^2}$	

TABLE I (CONTINUED)

Investigator	Correlation Proposed	
Kawasaki et al. (25)	$Nu = 0.0295\,(Ga \cdot Ku \cdot Pr)^{1/4}\,Re_v^{1/2}$	(2.15)
	where	
	$Ga = \frac{D^3 \rho^2 g}{\mu^2}$ Galileo number	
	$Ku = \frac{\lambda}{Cp\ \Delta T_f}$ Kutateladze number	
	$Re_v \equiv$ vapor Reynolds number	
	All liquid phase properties are volume averaged	
Ponter and Diah (35)	$h = \dfrac{h_o}{1 - 1.99\times10^4 \left(\frac{\Delta\sigma^3\ \Delta\rho_l}{\mu_l^4\ g}\right)^{-0.413} \left(\frac{\lambda_l\ \mu_l}{k_l\ \Delta T_f}\right)^{-0.286}}$	(2.16)

TABLE I (CONTINUED)

Investigator	Correlation Proposed	
	for condensation on copper surface	
	$$h = \frac{h_o}{1 - 0.047 \left(\frac{\Delta\sigma^3 \Delta\rho_l}{\mu_l^4 g}\right)^{0.143} \left(\frac{\mu_l \lambda_l}{k_l \Delta T_f}\right)^{0.359}}$$	(2.17)
	for polytetrafluoroethylene surface	
Somi Reddy et al. (41)	$$h = h_w \cdot 0.049 \, (\Delta T_f)^{0.882}$$	(2.18)
	$$h = 3.63 \left(\frac{h_o v_o + h_w v_w}{v_o + v_w}\right)^{0.887}$$	(2.19)
Akers and Turner (1)	$$h = 0.8 \frac{w_w \lambda_w h_w + w_o \lambda_o h_o}{w_w \lambda_w + w_o \lambda_o}$$	(2.20)

TABLE I (CONTINUED)

Investigator	Correlation Proposed	
	$h \left(\frac{\mu_o^2}{k_l^3 \rho_l^2 g}\right)^{1/3} = 1.47 \left(\frac{4\Gamma}{\mu_o}\right)^{-1/3}$	(2.21)
Bernhardt et al. (7)	$h = \frac{h_o v_o + h_w v_w}{v_o + v_w}$	(2.22)

drops to join the adjacent film of water at the boundary of the two films. Organic liquid condenses on the water film in the same manner, and joins its adjacent film.

Flow Type 4 (double dropwise) - Neither liquid wets the condenser surface; dropwise condensation of both components occurs.

Flow Type 5 - An intermediate between flow type 1 and 3. The organic liquid forms a continuous film on the condenser surface with small drops of water in its outer surface, much as in case 1, but at some point the surface is wet by isolated large drops of water which cling while the organic film flows over them. These drops finally become detached and join other water drops on the outside of the film, or they become large enough to be forced slowly down the condenser surface as a result of the flow of film past them.

Flow Type 6 - The converse of flow type 5, with water as the film.

Since the condensate flow mechanism is expected to govern the rate of heat transfer across the condensate, the above-mentioned flow mechanisms and other possible ones are analyzed in Chapter V from the point of view of heat transfer.

Investigations Using Vertical Tubes

Hazelton and Baker (20) started with a theoretical development based on Nusselt's equation. With this, they were not able to correlate the data successfully and empirical correlations were arrived at based on the theoretical work. The equipment used by Baker and Tsao (4) was modified for studying condensation on the outside of a vertical tube. Mixtures studied were steam with benzene, toluene and chlorobenzene. They also proposed a correlation for the data available for horizontal tubes. The correlations of Hazelton and Baker (Equation 2.1, 2.2) are dimensionally inconsistent, and should be used only with the English (U.S. Customary) system of units.

Patterson et al. (32) worked with a heptane-water mixture at low water contents by injecting steam into heptane. There was no attempt made to control the composition of the mixed vapors. The water was observed to condense in a dropwise manner and the heptane formed rivulets or film. No correlation was proposed to calculate the condensing coefficients.

Cooper et al. (14) presented data on ethyl acetate-isopropyl alcohol eutectic mixtures. They reported that the condensing coefficients were higher for the eutectic than those obtained for pure components. They also presented data on a butyl acetate-steam mixture. In this case, the condensing coefficients were found to be of intermediate values compared to the two pure component condensing coefficients. Condensing coefficients decreased with increasing film temperature difference. Bernhardt (6) pointed out that the butyl acetate used by Cooper et al. was only 91 percent pure, and hence the results are of questionable value.

Edwards et al. (17) studied condensation of styrene and butadiene with steam on the inside of a vertical tube. They used eutectic compositions and found that the condensing coefficients for the butadiene-steam mixture matched quite closely with McAdams' (29) observation which gives 20 percent higher values than Nusselt's theory. However, the data for the styrene-steam system did not agree with McAdams and they recommended a correlation to be used for that system only. In the McAdams equation they used physical properties and values of surface loading of the pure organic component only.

Tobias and Stoppel (44) studied eutectic mixtures of water with toluene, benzene, carbon tetrachloride, n-heptane and cyclohexane.

Initially they tried to fit the data using the Hazelton-Baker equation (Equation 2.1). Being unsuccessful, they proposed a modified equation (Equation 2.4). The equation shows considerable deviation in some cases and an explanation is given by the authors. The following anomalies resulting due to the nature of the equation are expected. For the limiting case of water condensing alone the numerator becomes infinite and for the organic condensing alone the denominator becomes negatively infinite. Furthermore, the denominator may become zero for a case of low water percentage in the condensate. Hence a range of 8 to 98 percent water by weight is recommended.

Krishnaiah and Satyanarayan (28) studied condensation of water with benzene, toluene, chlorobenzene and carbon tetrachloride on the outside of a 1/2 in. copper tube. The compositions were non-eutectic and were varied deliberately. The organic film was observed to completely wet the surface and water formed drops on the organic film. Parallel lines of data are plotted on a log-log scale for the benzene-water and the toluene-water mixtures for condensing coefficients versus the film temperature difference. A modification of Bernhardt's correlation is suggested for the mixtures. Another correlation involving the condensate weight fractions is also proposed.

Ponter et al. (36) studied condensation on the outside of an oxidized copper tube. The mixtures studied were eutectics of water with carbon tetrachloride, trichloroethylene, benzene and cyclohexane. They reported a consistently higher condensing coefficient in comparison with Bernhardt's correlation. They also report that the exponential dependency of the condensing coefficient on the film temperature difference varies with the substance condensing.

Investigations Using Horizontal Tubes

In 1933 Kirkbride (27) published the first reported work on the subject of binary condensation. A horizontal internally-cooled steel tube was used as the test surface. The two systems studied were steam-benzene and steam-"cleaners naphtha". It was recognized that "drop forming condensation" may have occurred, complicating the problem. An equation was proposed to calculate the average condensing coefficient from the pure component condensing coefficients, using the condensing heat loads of the two components as the weighting factors. When calculating the pure component condensing coefficients, the properties of the pure components were used along with the "film temperature difference" observed during the binary condensation. No attempt was made to ensure that the vapor composition was eutectic. In fact, the vapor entering as well as leaving the test section was reported to be superheated, and the condensate compositions show wide variations. The temperature variation along the length and around the periphery of the tube was ignored.

Baker and Mueller (2,3) studied condensation of steam along with benzene, toluene, mixed heptanes and trichlorethylene as the organic substances. Even though they attempted to get eutectic mixtures, a substantial amount of the data reported are for non-eutectic compositions. After a series of mathematical manipulations, they reported an equation using condensing heat loads of the two components. The equation is dimensionally inconsistent and should be used only with the English system of units. It was concluded that 'a strict theoretical attack' on the problem was not possible and the thermal and physical properties of the liquids as well as the surface properties would be important. The importance of temperature variation around the tube periphery was also emphasized. Baker and Mueller indicated no change in the condensing coefficient with change in film temperature in the range of 7 to 70°F.

Baker and Tsao (4) used an electrical resistance method similar to the Wheatstone bridge circuit to measure the surface temperature. They used an average value of the temperature over the entire length of the tube as well as around the periphery. The temperature drop across the wall was calculated from the heat load and was assumed to be uniform around the periphery. They condensed benzene, toluene, chlorobenzene or trichloroethylene along with water on copper tubes. The proposed equations are highly empirical and predict absurd results if the parameters are used beyond their suggested range.

Patton and Feagan (33) studied turpentine-water condensation on a horizontal copper tube. The condensate pattern was reported to be film-dropwise, with the turpentine condensing as the film. The condensing coefficient was plotted against the film temperature difference and showed a relationship of $h \propto (\Delta T_f)^{-0.55}$.

Stepanek and Standart (42) attempted a theoretical development but could not go beyond a semi-theoretical equation because of mathematical difficulties. Bernhardt et al. (7) pointed out that the Stepanek and Standart equation breaks down for pure substances and predicts a zero condensing coefficient for an intermediate composition. Also, it does not fit well with the data of others. The mixtures studied were benzene, toluene, dichloroethane or chlorobenzene along with steam. Stepanek and Standart also claim that the dependence of the condensing coefficient on the film temperature difference varies with the mixture.

Sykes and Marchello (43) condensed steam along with carbon tetrachloride or toluene. The first equation (2.13) proposed by them predicts the same condensing coefficient as for pure organic, if the density of the organic phase is same as that of water. However, there are no data available to support this prediction. The organic liquid density was used to correlate the condensing coefficient with the film temperature. This dependence on organic density was found not to be always true and later was associated with the condensing patterns by Polley and Calus (34). The second correlation (2.14) by Sykes and Marchello is based on the two film model which assumes the organic film to be adjacent to the wall and the water film to be on top of the organic film. This was expected to predict the minimum condensing coefficients but some experimental data were lower than the two film model prediction. Their third equation based on the nucleation model was most successful over a wide range of systems. It assumes an organic film on the surface and water drops nucleating on the organic film. The bulk of the heat transfer resistance is assumed to be concentrated in the nucleation process.

Kawasaki et al. (25) analyzed simultaneous mass and heat transfer effects during immiscible mixture condensation using Maxwell's equations for mass transfer. The proposed equation is similar to the Nusselt equation. The dimensions of the condensation tube are unclear, but it is apparent from the sketch of their apparatus that the vapor flowed across the tube with the possibility of vapor shear influencing the results. Also, only one thermocouple each is shown for measuring the surface and vapor temperature. The tube could not be rotated on its axis and hence the effect of temperature variation around the periphery of the tube is neglected. Average condensate properties were used: the thermal conductivity, density and viscosity are averaged based on the volume fraction and the specific heat is averaged based on weight fraction.

Salov and Danilov (40) studied the temperature variation around the periphery of a horizontal tube and along the length of a vertical tube, using mixtures of benzene, toluene, trichlorethane, heptane or gasoline with steam. Analytical equations are proposed for the prediction of local and mean values of condensing coefficients.

Bernea and Mizrahi (5) argued that correlating the condensing coefficient to the film temperature difference is incorrect. Their suggested relation is:

$$h \propto \left(\frac{Q}{A}\right)^{1.26} \qquad (2.23)$$

They studied the condensation of steam with kerosene (boiling range 200 to 250°C). Substituting (Q/A) by ($h\Delta T_f$) leads to $h \propto (\Delta T_f)^{-4.85}$. Their work involves back-calculating the condensing coefficients from the overall heat transfer coefficients. The coolant side heat transfer coefficient was calibrated to the coolant Reynolds number for a particular value of Q/A. This was then used for all further calculations at various values of Q/A. This approach is questionable due to its dependency on a fixed coolant side heat transfer coefficient.

Yusufova and Neidukht (45) studied complete and partial condensation of a gasoline-steam mixture inside horizontal tubes, with vapor velocities up to 15 m/s (50 ft/s). The gasoline density was 0.7405 gm/cm^3. The tubes were made from two different types of steel, brass and aluminum. They reported that the condensing coefficient is independent of the tube material and increases with an increase in the heat flux Q/A. It was also concluded that the "degree of finish" of the tube surface has a considerable effect on the condensing coefficient. They report a proportionality as:

$$h \; \alpha \; (\frac{Q}{A})^{1.1} \tag{2.24}$$

Substituting for (Q/A) by $(h\Delta T_f)$ will result in:

$$h \; \alpha \; (\Delta T_f)^{-11}$$

They also presented an exponential curve showing decreasing condensing coefficient with increasing film temperature difference. In their work the vapor velocities are likely to affect the condensing patterns and hence may affect the condensing coefficients. Therefore, their data are not suitable to study the effect of one parameter at a time.

Ponter and Diah (35) condensed eutectic mixtures of water with benzene, carbon tetrachloride, 112-trichloroethylene and cyclohexane. The condensation occurred on a 1 in. diameter copper tube and a Teflon®-coated 1 in. diameter copper tube. They reported condensing heat fluxes equal to or higher on the Teflon®-coated surface than the plain copper surface, for the same temperature driving force. This was attributed to the faster removal of the water from the Teflon® surface, resulting in reduced heat transfer resistance. This phenomenon compensated or sometimes exceeded the negative effect due to the low thermal conductivity of the Teflon® coating. No visual observations of the condensate flow patterns are reported. One correlation each is recommended for condensation on the copper and the Teflon® surface. However, they conclude that Bernhardt's correlation fits the data most successfully.

Somi Reddy et al. (41) condensed non-eutectic mixtures of benzene, toluene, monochlorobenzene, carbon tetrachloride, trichloroethylene and n-heptane with water outside a 1/2 in. copper tube. The mixture compositions varied greatly. The weight fraction of water in the condensate was in the range of 20 to 80 percent. The ratio of the mixture condensing coefficient to the steam condensing coefficient is correlated with the weight fraction of water in the condensate as well as the film temperature difference. This shows a large amount of scatter. The condensing coefficient is also correlated to the film temperature difference. Finally one separate modification of Bernhardt's correlation is recommended for each of the organic substance.

Investigations Using Other Geometries

Akers and Turner (1) studied various mixtures condensing on a vertical "cold finger" of brass, 2.5 in. diameter and 3 in. long. Their data are for mixtures within 2 percent of eutectic compositions most of the time. They have noted a number of interesting observations in their experimental procedure. Steady state conditions were sometimes reached quickly while some cases took several hours.

Akers and Turner introduced the Harkin and Feldman (19) concept of spreading coefficients. For the case of two liquids A and B, the spreading coefficients γ_{AB} for A spreading over B and γ_{BA} for B spreading over A are defined as:

$$\gamma_{AB} = \sigma_B - \sigma_A - \sigma_{AB} \quad (2.25)$$

and

$$\gamma_{BA} = \sigma_A - \sigma_B - \sigma_{AB} \quad (2.26)$$

If the spreading coefficient $\gamma_{BA} > 0$, then liquid B will spread over drops of liquid A and form a film over them. For $\gamma_{BA} < 0$, liquid A will form drops but the liquid B will form a film around them and the drops of liquid A will stand exposed to the vapor. Akers and Turner state that, though it is not possible to predict the mechanism of two phase condensation accurately, the spreading coefficients are certainly indicative.

For predicting the condensing coefficients, Akers and Turner have proposed two equations. For the film-drop and the film-lens mechanisms, they suggest the use of Nusselt's equation. The viscosity of the "surface wetting" liquid is used. The density is averaged based on the weight percent and the thermal conductivity is averaged based on the volume percent of the liquids in the condensate. All their data lie within 30 percent of the predicted values. For channeling flow, their data showed a closely parallel trend, but were 20 percent below the prediction by the Kirkbride equation. They recommend using another equation for this flow pattern.

The work of Bernhardt et al. (7) is unique in terms of visual observations and experimental techniques. A vertical gold-plated copper plate was used as the condensing surface. Detailed motion pictures of the mechanism of condensation were taken. An electrical probe assembly and a dye technique were used independently to prove that in the film-drop and the film-lens mechanisms, the film was always made of the organic phase and the discrete drops were of water. Before this study, it was only suggested and claimed that the film would be organic. The motion pictures show that large standing drops of water as well as the surrounding organic film were both in contact with the metal surface, and also exposed to the vapor. This is a four phase non-equilibrium configuration between solid-liquid-liquid-vapor. Bernhardt et al. state that no correct theoretical treatment is available, hence empiricism is necessary for predicting the condensing coefficients. Using a "shared surface model", a simple equation is recommended. This equation calculates an average of the pure component condensing coefficients based on the volume fractions of each phase in the condensate.

Boyes and Ponters (9) studied the behavior of organic and aqueous phases in contact with a copper as well as a Teflon® surface. The experimental conditions were static. There was no continuous heat removal from the solid surface and the liquid phases were not drained out. Liquid drops were introduced on the surface using needles. They found that the surface forces as well as the bouyancy forces play an important part in determining the hydrodynamic behavior. They have presented plots of the condensing coefficients versus film temperature difference without recommending any correlation.

Other Related Studies

Kapitza (22,23,24) analyzed the wavy flow pattern in the liquid flowing down a vertical surface. It was then applied to condensate flow in the presence of a moving vapor phase. The wave amplitude, shape and phase velocity calculations are given. Photographs of the wave pattern for water-alcohol studies are given.

Brauner and Maron (11) have modeled the wave flow of film on an inclined surface. Theoretical development leading to wave speed, amplitude and frequency calculations is done. The wave was divided into three parts, the front, the back and the substrate. Based on the film Reynolds number, the fraction of liquid flowing in each part of the wave was calculated.

For a pure component, Dukler (15,16) has derived the dependency of the condensation number on the condensate Reynolds number as a function of the liquid Prandtl number and interfacial friction. Numerical solutions in the form of plots are presented for Reynolds numbers above 100. At zero interfacial friction, the deviation from the Nusselt equation is shown to be dependent on the Prandtl as well as the Reynolds number. For Prandtl numbers in the range of 1 to 10 the predicted condensation number is always higher than the Nusselt theory.

Blangetti and Schlunder (8) studied pure steam condensation at vapor Reynolds numbers in the range of 15000 to 25000. They reported condensing coefficients intermediate between those predicted by Nusselt's and Dukler's equations.

Summary

The mechanisms of condensation as described by Hazelton and Baker are given above. In practice, the only mechanisms which have been observed are those of types 1, 3 and 5. The types which have water as a continuous film and organic as the drops (types 2 and 6) are not likely to be realized with any common organic components due to the lower surface tension of the organics. This is consistent with the spreading coefficient theory of Harkin and Feldman (19). The double dropwise model (type 5) might be possible with water and selected organics condensing on a low energy surface, such as Teflon®, although this has not been reported to have been achieved in practice.

There are many questions still to be answered as to the effect of certain variables which may be expected to influence the condensation mechanism of steam-organic mixtures. Film temperature difference is one of the very important ones. Another parameter not considered by many workers is the density ratio. This is of considerable importance, particularly on horizontal tubes, where gravity is likely to play an important role in the drop behavior. Different heat transfer effects would be expected for drops which touch the metal surface as opposed to those which float on the film.

Relatively little work has been done on the condensation of organic-organic immiscible mixtures. This is perhaps due to the greater commercial interest in the organic-steam mixtures. The only reported data of this kind are those of Akers and Turner (1) on heptane-methanol mixtures and Cooper et al. (14) on ethyl acetate-isopropyl alcohol mixtures. Akers and Turner (1) describe the mechanism as being film-lens type, but do not state which component formed the film and which formed the lens. The equation used to correlate the data was accurate within 25 percent.

There is no published work on the effect of the presence of non-condensible gases on the condensation process. This is not at all surprising since the mechanism for the case of pure component mixtures itself is not clearly understood. The introduction of a non-condensible gas would complicate the mechanism further.

The only reported work in which high vapor velocities have been used in that of Yusufova and Neidukht (45). The components used were steam and a petroleum fraction. No attempt was made to analyze the effect of vapor shear. No data exist on a single component organic condensing along with steam, at high vapor velocities. Hence the effects of vapor shear are unknown.

No data are available for the condensation of immiscible mixtures on tube banks, nor has there been much work published on the in-tube condensation of binary mixtures. Obviously, further work is required in all the above-mentioned areas before a fuller understanding of the problem can be attained.

This work concentrated on obtaining reliable quantitative as well as visual data and developing a prediction method based on the observed condensate flow mechanisms.

CHAPTER III

APPARATUS

Introduction

The apparatus was designed and constructed to obtain quantitative (local heat transfer rates and coefficients) as well as qualitative (visual) data. Previous work (18) with other similar apparatus had indicated many experimental difficulties and these trouble spots were eliminated. The apparatus can be divided into four broad subsystems. These are the process fluid system, the coolant system, temperature measurement and photography.

A schematic flow diagram of the apparatus is shown in Figure 2. Using steam from the 60 psi steam line, single or multiple component vapors are generated in the boiler. The vapors are carried by a 1 in. x 20 BWG, 304 SS tube to the test cell. The test cell has a condensing surface and glass window for observation. The condensate is removed from the bottom of the test cell through a three-way valve and returned to the liquid accumulation chamber. The uncondensed vapors are also removed at the bottom of the test cell and carried to an auxiliary condenser by a 1/2 in. x 20 BWG 316 SS tube. The vapors are completely condensed and the condensate drained to the liquid accumulation chamber through another three-way valve. The two three-way valves are used to redirect the condensate flow for measurement. The condensate from the

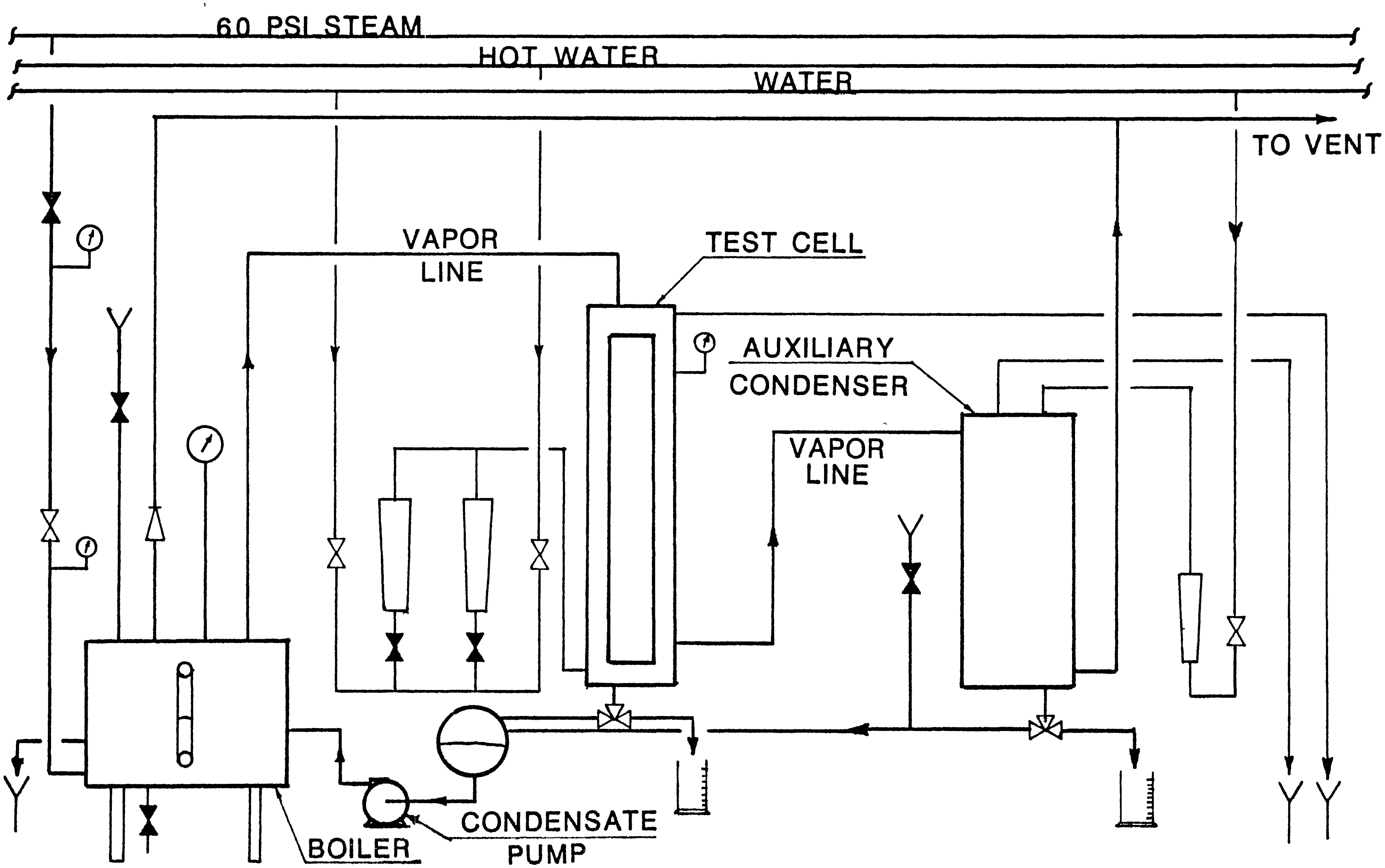

Figure 2. Schematic Flow Diagram

liquid accumulation chamber is pumped back to the boiler using a peristaltic pump.

The cooling water is drawn from the cold and hot water supply lines. For the test cell, the cold and hot water streams are combined to obtain the desired coolant inlet temperature. This is useful in varying the condensing heat flux under investigation in the test cell. The auxiliary condenser is supplied with cold water only. The coolant flow rates to the test cell and the auxiliary condenser are monitored using rotameters. The auxiliary coolant flow uses a single rotameter. The test cell coolant line has two parallel rotameters for high and low flow ranges. A detailed description of all the components is given below.

A plexiglass protective shield was mounted on the equipment panel in front of the boiler and another one in front of the test cell. These shields were not air-tight, but were deployed to intercept any hot fluid splashing in case of an accident.

The water used in the experiments was locally distilled in the Chemical Engineering Unit Operations Laboratory. The toluene and R-113 used were reagent grade chemicals, obtained from Fisher Scientific Company.

Process Fluid System

The Boiler

The boiler is a copper chamber with a steam coil located at the bottom. Figure 3 illustrates the boiler dimensions. The steam coil is a 3/8 in. copper tube arranged into three rows of heat transfer surface. The inlet and the outlet are located on the side. The front

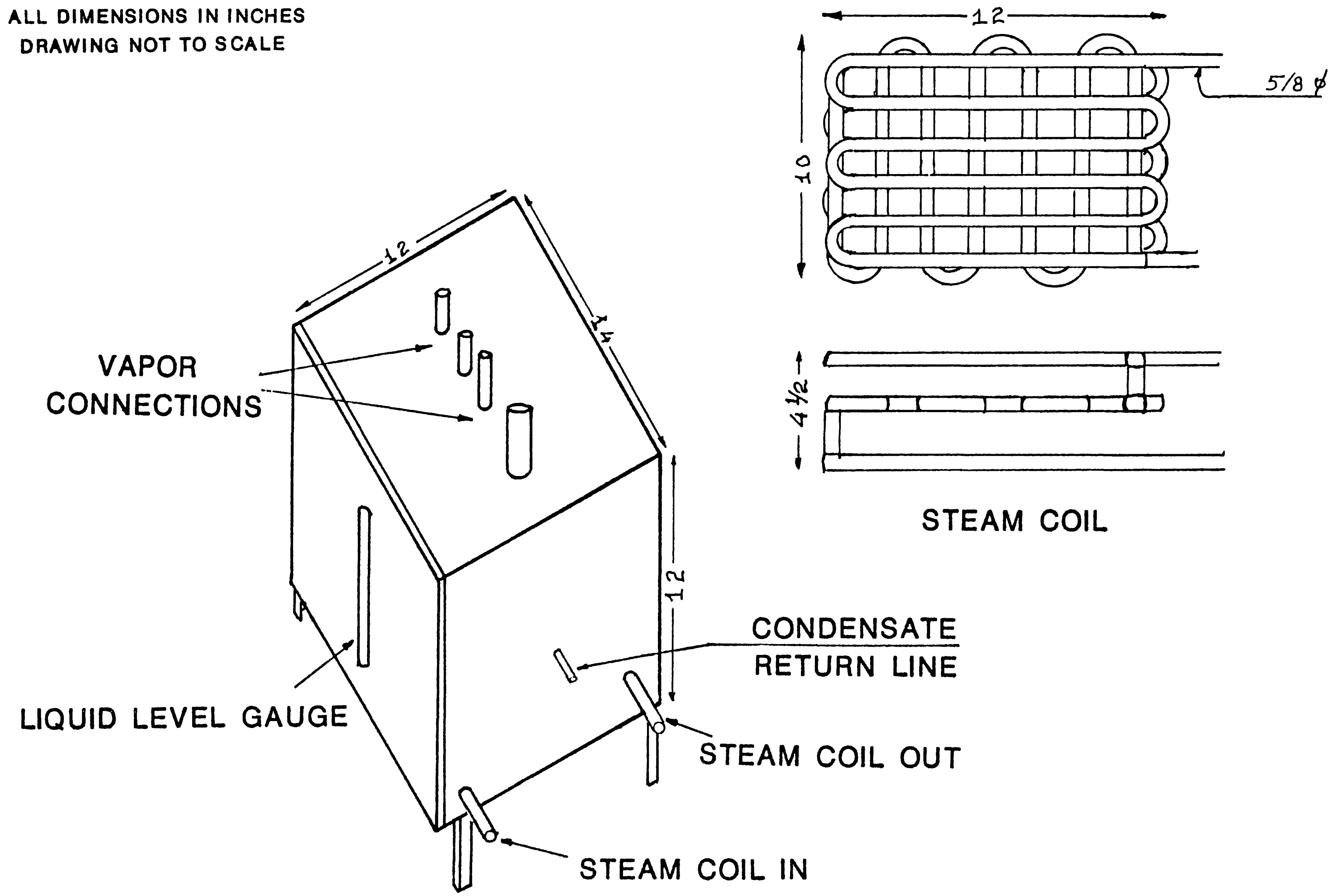

Figure 3. The Boiler

side of the boiler has a removable cover. The cover was designed to facilitate coil cleaning whenever necessary. The cover is made of 1/4 in. thick aluminum and attached to the boiler using 16 machine screws, 1/4 in. diameter. A silicone sealant gasket is used to prevent leaks at the cover plate. A liquid level gauge is attached to the cover. This level indicator is useful in maintaining the liquid level above the heating coils in the boiler.

There are four outlet connections on the top surface of the boiler. These connections consist of copper tubes joined to the boiler surface. A 1 in. tube is used for the vapor flow from the boiler. The other three connections are 1/2 in. tubes. Of these, one is connected to a pressure gauge. The pressure gauge is a bourdon type made by the U.S. Gauge and has a range of 30 in. Hg vacuum to 15 psig. The third outlet is connected to a 4 ft. long 1/2 in. SS vertical tube with a valve at the end. This tube may be used to fill the boiler with liquids before startup and works as a backup liquid inlet during operation. Inside the boiler, this tube extends down to the top of the heating coils, assuring that it is submerged in liquid during operation. This is a precaution against vapor escaping during operation and vapor lock during operation in the long tube. The fourth boiler outlet is connected to the vapor escape line going to the ventilation hood, through a check valve. The crack open pressure of this check valve is set at 5 psig, assuring no vapor loss during normal operation.

The boiler has a drain outlet at the bottom surface. The drain is kept closed using a gate valve. The boiler legs keep the boiler bottom surface 8 in. above the floor and make the drainage operation possible. On one side of the boiler, a 1/4 in. x 20 BWG copper tube is connected for condensate return. Inside the boiler, the tube extends to the bottom of the boiler below the heating coil. The extended tube assures no vapor lock in the condensate return line during operation.

The Test Cell

The test cell consists of four layers of plates bolted together to form two channels along the length of the cell. Figure 4 illustrates the exploded view of the assembly. All the plates are made of 304 SS. The back plate, along with the cold surface of the condensation plate, form the coolant channel. A detailed description of the coolant channel is given later in this chapter. Figure 5 shows the condensation plate. The dimensions of the plate are big enough to eliminate any entrance effects. There are five thermocouple stations along the length of the plate. Each station consists of three holes for thermocouples. All holes are 1-1/2 in. deep, drilled parallel to the condensing surface.

The rectangular plate in front of the condensation surface forms the vapor channel. A detailed view of the vapor channel is shown in Figure 6. The vapor inlet is located at the top end of the vapor channel. This is a 3/8 in. FPT connection. The vapor outlet connection is located on the side of the vapor channel near the bottom. This is also a 3/8 in. FPT connection. The condensate withdrawal connection is located at the bottom of the vapor channel, nearer to the condensing surface. This connection is 1/4 in. FPT. A U-tube is connected to the inside of the vapor inlet connection. This is to facilitate even distribution of the incoming vapor across the flow cross section. The vapor channel plate is provided with one 1/8 in. diameter continuous

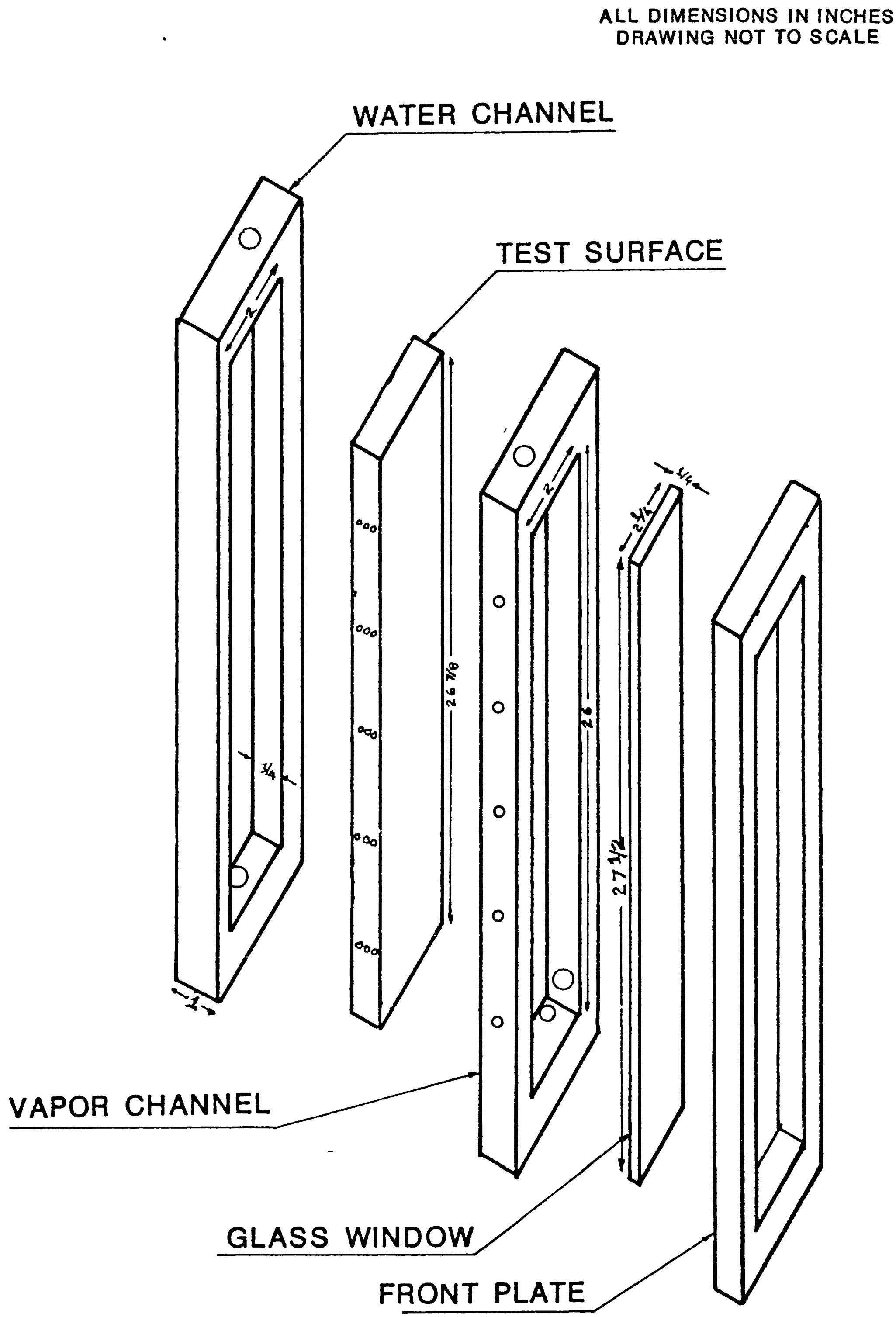

Figure 4. The Test Cell

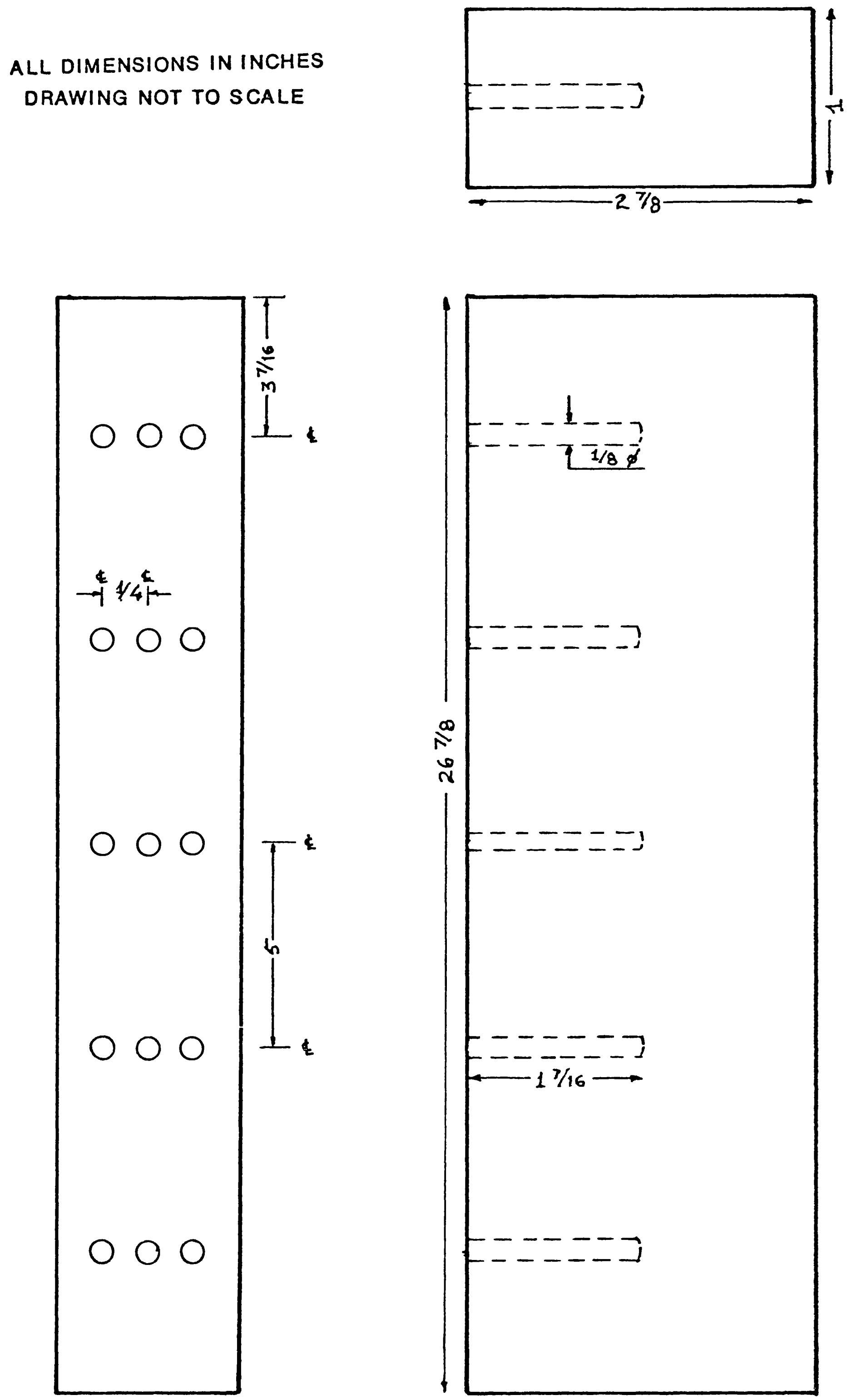

Figure 5. The Condensation Surface

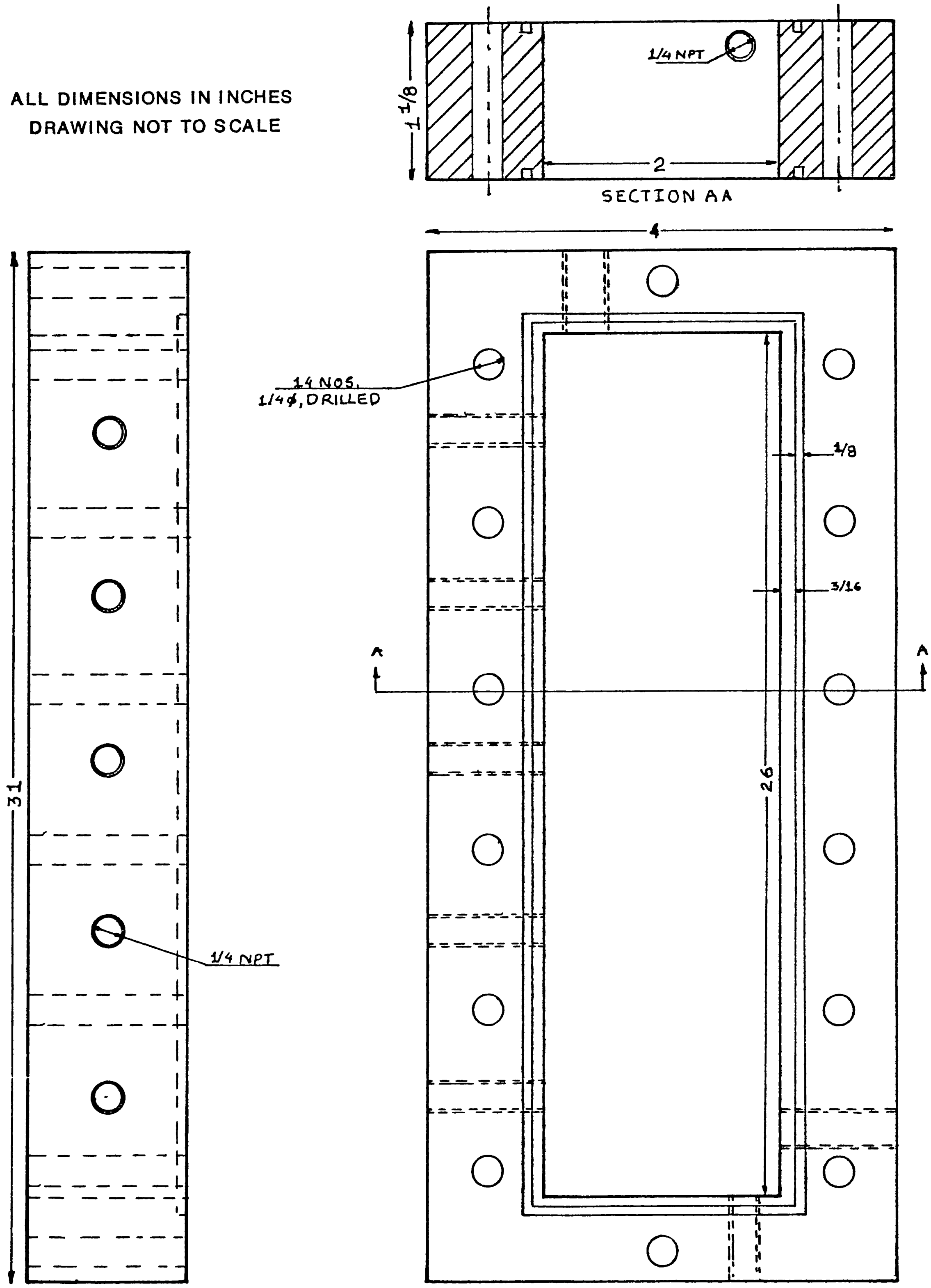

Figure 6. The Vapor Channel

groove each, on both sides for the gasket. The gasket is made of Viton® string, cut and joined to form the proper size of gasket ring.

A Pyrex® glass window is placed on the front side of the vapor channel. Two strips of automobile window defogging unit are glued to the glass on the outside surface. These are connected to the two bus bars near the top and bottom ends of the glass. The top plate of the test cell is placed on top of the glass window. This plate also has a gasket groove. In addition to the gasket ring, a layer of silicone gasket sealant is spread outside the gasket grooves on both sides of the glass surface, before bolting the plates together. This is done as an extra precaution against leakage from the vapor channel. In order to control the compressive stresses independently, the vapor channel plate is bolted to the back plate with 14 machine screws, 1/4 in. diameter. The condensation plate is sandwiched between these two plates. Then the top plate is bolted to the vapor channel plate using 14 machine screws, 1/4 in. diameter. The glass window is sandwiched between these two plates.

The Auxiliary Condenser

The cylinder is constructed using sheet metal, with a longitudinal weld. The top and bottom surfaces are sealed off using circular plates. The cooling coil is an 1/2 in. diameter copper tube with several feet of coil length inside the cylinder. Both the inlet and outlet of the coil are connected at the top surface of the condenser. The vapor to be condensed enters the shell side from the side, near the top. The connection is a 1/2 in. diameter copper tube. The condensate is drained from the bottom using a 1/4 in. diameter tube. The condensate passes through a three-way valve and is drained to the accumulation chamber. An opening is provided near the bottom of the condenser for the non-condensibles and uncondensed vapor to leave the system. This tube is connected to a line going to the ventilation hood.

The Condensate Transport System

Condensate from the test cell, as well as the auxiliary condenser, is drained to the condensate accumulation chamber. This chamber is a 5 in. diameter Pyrex® glass spherical container, with an opening at the bottom. The condensate from the test cell flows to this chamber through a three-way valve. There is a separate three-way valve for the condensate from the auxiliary condenser. The connections between tubes are made using a 1/4 in. ID Viton tubes. A peristaltic pump is used to draw the condensate from the accumulation chamber and pump it to the condensate return line on the side of the boiler. The pump speed can be varied using a variable resistance speed controller. One more line is connected to the condensate accumulation chamber for adding fresh or recycled liquids to the system. This line is kept closed when not in use. Using the three-way valves, the condensate flow can be redirected outside for measurement.

Cooling System

The cold water line is connected directly to the auxiliary condenser through a flow control valve and an open loop system is used. A Fisher and Porter rotameter (Tube No. FP-3/4-27-G-10/80) is used to measure the water flow rate to the condenser. A 1/2 in. diameter tube is used throughout for the water flow. The primary coolant system uses two Fisher and Porter rotameters (Tube Nos. FP-1/2-35-G-10/55 and FP-1-1/2-27-G-10/55). These are connected in parallel and used for different ranges of flow. The coolant is a mixed flow of the hot and cold supply line water. The flow rates are adjusted in order to obtain necessary coolant temperature. This is important in controlling the heat flux in the test cell. The water flows through a 1/2 in. tube to and from the coolant channel of the test cell.

The coolant channel in the back of the test cell is 2 in. wide and 3/4 in. deep and runs along the length of the condensing surface. The inlet and outlet connections are 3/8 in. FPT. Brass connectors are used to connect the inlet and outlet tubes. The water flows from the bottom towards the top of the channel. This is done to assure no air lock in the coolant channel. The coolant leaving the test cell is also passed to the drain.

Temperature Measurement

There are 28 thermocouples used in temperature measurement. All are made of copper-constantan junctions (type T). The four thermocouples used for coolant inlet and outlet temperature measurement are ready-made from Omega. For all other thermocouples, the thermocouple wire was made by Omega Engineering and the thermocouple junctions were made in the laboratory using a thermocouple welder. The wire used was either 24 gauge or 28 gauge. Four thermocouples were used to measure the vapor temperature. At the five stations in the condensing plate, three thermocouples were used at each station. Five thermocouples were placed in the coolant channel behind the measurement stations on the condensation plate. A multijunction switch was used to connect one thermocouple at a time to the Omega type T digital temperature readout. This temperature measurement readout has an internal cold junction compensator.

Photography

In order to observe the condensation patterns it was necessary to keep the glass window on the test cell fog-free. Several methods were tried to achieve this. The best method seems to be using a chemically-coated glass. The coating being electrically conductive, a small voltage may be applied across the length of the glass surface. This would provide sufficient heat to prevent condensation of the vapor in the vapor channel on the inside of the glass surface. Attempts to obtain such a chemically-coated glass with adequate strength were unsuccessful. Infrared flood lamps were tried to keep the glass hot, but resulted in non-uniform heating of the glass. Also the condensing surface was exposed to outside fluxes, unaccounted for in the heat transfer calculations.

Finally, two parallel strips of automobile window defogger were planted on the glass window. Two bus bars were created at the two ends of the glass and the strips connected to them. A small voltage was applied to heat the strips. The voltage was controlled using a power rheostat. It was possible to provide just sufficient heat to the glass window to keep it fog-free. This method proved to be satisfactory.

Still photography was done using a Nikon model F camera. A Nikon motor drive was used along with the camera. Two Konica rings #K2 and #K4 were used between the objective lens and camera body. This facilitates focusing the camera at distances of the order of a few inches. The film used was Kodak Tri-X (400 ASA) black and white. Two flood lights were used to illuminate the condensation surface. The camera, as well as the lights, were mounted on a traveling light stand for easy movement along the length of the condensing surface. A plexiglas protective sheet was placed outside the glass window during normal operation. This sheet was temporarily removed while using the camera. After several trials a shutter speed of 1/1000 sec and an aperture size (f/stop) 5.6 was found to be satisfactory.

For motion picture photography, a Bolex 'H16 Reflex' 16 mm camera was used. The objective lens was 75 mm focal power and was used with a 10 mm focusing ring, similar to the one used with the Nikon still camera. The same lighting arrangement was used. The film used was Kodak black and white 4-X reversal type, speed 320 ASA. The filming was done at a standard rate of 24 frames per second. The aperture size (f/stop) was set at 16 due to the relatively slower exposure rate. The camera was driven by an electric motor at a uniform speed and 100 ft rolls were used.

CHAPTER IV

EXPERIMENTAL PROCEDURE

Pre-start Up

The boiler was hydraulically pressure tested up to 15 psig. A set of check valves were connected to one of the exits in series. Each valve had a spring with a crack open pressure of 8 psig. All other openings to the boiler except one inlet were closed. Water was pumped to the boiler using an Eastern MD-11 centrifugal pump through the open inlet. The check valves opened up and water started flowing out through them when the pressure in the boiler reached 15 psig. The water pressure inside the boiler was maintained at 15 psig for four hours. No leaks were detected. A similar pressure test was done on the test cell and the auxiliary condenser using compressed air. The test was run at 5 psig.

The accuracy requirement of the pressure gauges is not very stringent. The gauges were tested and found to be satisfactory. The rotameters were checked using water. The factory calibration was found to be satisfactory. Initially, the thermocouples were calibrated using a platinum resistance thermometer. The maximum error in each thermocouple was found to be equal to or less than 0.3°F These errors were temporarily neglected and later accounted for in the deviation optimization program as described in the next chapter.

The pre-start up checks involve keeping the liquid level in the boiler above the top layer of the heating coil. A red mark is made on the liquid level indicator corresponding to the coil top. If more than one liquid phase is present in the boiler, the level of the heavier liquid must be above the coil top. This helps in creating an eutectic vapor mixture.

Start Up

The temperature indicator is turned on at least half an hour before the first temperature reading is taken. The coolant flow valves are opened and the water flow is started for both the test cell and the auxiliary condenser. The steam valve upstream of the boiler is opened 4 to 5 turns and the downstream valve is opened about 3 to 4 turns. The block valve in the steam supply line is then opened to allow steam to flow through the boiler heating coil. The upstream valve is used to control the steam pressure in the heating coil and the downstream valve is used to control the flow rate. Based on the substance to be boiled, 5 to 15 minutes are required before vapor starts flowing to the test cell. Initially it is necessary to open up the three-way valve all the way for the condensate drainage to start towards the accumulation chamber. The condensate pump is started as soon as the accumulation chamber starts receiving liquid from the test cell and the auxiliary condenser. Electrical power is now supplied to the glass defogging strips. The voltage required is 5 to 10 volts. This voltage is controlled such that excessive heating of the glass does not occur. This is indicated by the absence of any condensate flowing on the inside glass surface. At the same time any of the liquid droplets splashing on to the glass surface should vanish very slowly. Over-heating will evaporate such liquid droplets quickly and this extra heat can result in unknown effects on the data obtained.

Operation and Data Acquisition

Approximately 30 minutes are allowed for the process to achieve steady state. During this period, the pressure in the boiler, steam line pressure, pressure in the test cell, coolant flow rates and the condensate flow rate are constantly watched for variations. The pressure in the boiler is kept below an arbitrarily specified limit of 2 psig. This results in the test cell pressure being below 1.0 psig. For most runs, the test cell pressure was between 0.0 and 0.2 psig. Higher pressures were necessary for high flux runs. The coolant flow rates are maintained such that the coolant exit temperatures from the test cell as well as the auxiliary condenser are well below the dew point of the vapor. In normal operation, no vapor escapes the auxiliary condenser and the condensate leaving is subcooled by several degrees. The three way valve for the test cell condensate flow is partially choked off so that only condensate can pass to the accumulation chamber and almost all the uncondensed vapor goes to the auxiliary condenser.

The following sequence is performed for acquiring data for a particular run. The pressure gauges are read for the steam line pressure, boiler, and the test cell. A mercury barometer is used to record the barometric pressure. The coolant flow rates for the test cell and the auxiliary condenser are recorded. The 28 thermocouple temperatures are recorded one by one using the digital readout meter. The condensing flow patterns are observed through the glass window. The three-way valve on the test cell condensate return line is turned so that the condensate can be collected in a graduated cylinder. A stop watch with a precision of 1/10th of a second is used to record the rate of condensate collection. The three-way valve is then returned to its normal position so that the condensate flows to the accumulation chamber. Similarly the condensation rate in the auxiliary condenser is measured. If necessary, the still or motion pictures can be obtained at this time. This completes one set of data. Any of the operating parameters such as the coolant inlet temperature or the vapor generation rate can now be changed, and the system allowed to run for approximately 30 minutes to achieve another steady state and another set of data can be obtained. Some sets of data were obtained without changing the process conditions, with an interval of 15 to 20 minutes. The almost identical values obtained confirmed that a steady state can be reached within a short time after changing the process conditions or after the initial startup.

Shut Down Procedure

In the course of normal shut down after obtaining data, the steam line block valve is shut off. This stops vapor generation in the boiler. After about 3 to 5 minutes, the amount of condensate draining to the accumulation chamber is negligible and the condensate return pump is shut off. The power to the glass defogging strips is then cut off. The coolant flow is continued for another 10 minutes. The condensation surface should be cooled substantially by then. When the hottest temperature at any of the 5 stations is less than 85°F, the coolant flow can be safely shut off. Any condensate accumulated in the chamber is then pumped back to the boiler and the valves upstream and downstream of the boiler in the steam lines are completely shut off. This completes the normal shut down procedure. If necessary, the boiler may be drained completely of the liquids after they have cooled down. Before adding new liquids to the boiler, it is imperative that the boiler should be completely dried of previous liquids. This can be achieved by establishing a continuous flow of air through the boiler for an extended period of time. For a more thorough cleaning, the system is run with distilled water for 1 to 3 hours and then drained and air-dried.

An emergency shutdown may be necessary due to several reasons such as loss of electrical power in the building, or a suddenly developed leak in the system. The first procedure in such cases is to shut off the steam to the boiler using the block valve. In case of leaks, these then should be isolated and flow towards these be stopped. The coolant, if not leaking, should continue to flow through the system until the system is cooled down. In case of loss of coolant, the steam should be immediately cut off and the power to the defogging strips and the condensate pump cut off. Under no circumstances should the boiler be opened or drained until the liquids inside are cold or proper equipment is available to handle hot liquids present in the boiler.

CHAPTER V

DATA ANALYSIS

Introduction

Initially, in order to test the apparatus, data were obtained for condensation of pure steam. At each station, the three temperature readings inside the condensation plate were used to obtain a linear temperature profile through the plate. The profile was then used to calculate the surface temperature at that location. The vapor temperature is measured and hence the temperature difference across the condensate film is known. The thermal conductivity of the condensation plate and the temperature gradient through it gives the heat flux through the plate. Hence the condensing coefficient can be calculated. The detailed calculations for each of the systems are presented in Appendices C through G.

Initial data reduction calculations were done for Runs 13 through 33. Substantial deviations were found in the results in comparison with the Nusselt theory. The most obvious reason for this inconsistency was thought to be that the thermocouple tips not being exactly at the center of the thermocouple wells or that the wells were not exactly where they ought to be. Small deviations in the thermocouple locations can result in substantial errors in the calculated surface temperature. There was no physical method available to evaluate this thermocouple displacement. An illustration of the displacements is given in Figure 7.

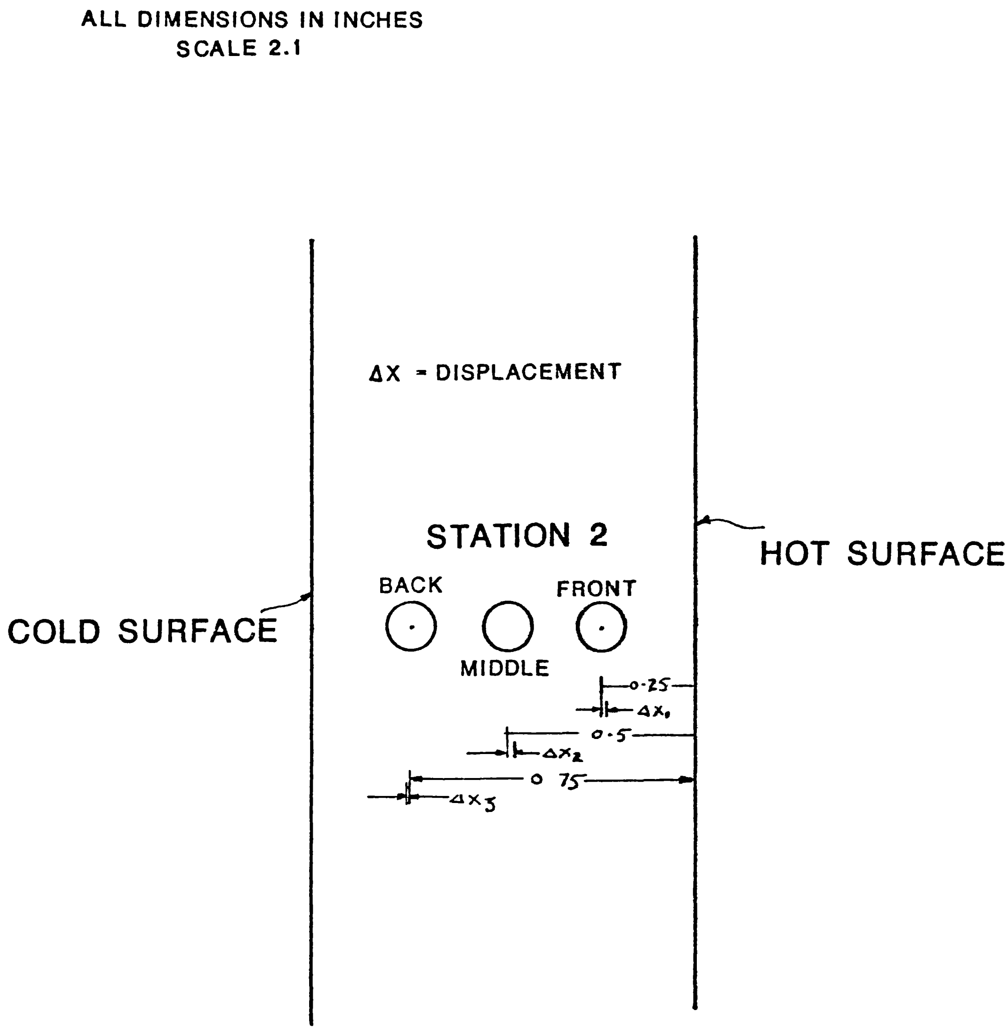

Figure 7. Thermocouple Station with Displacements

A non-linear optimization technique was used to calculate the displacement distance for each of the thermocouple inside the condensation plate. The Nelder-Mead (30) Simplex method is a suitable brute force technique for such purpose. This method is more intelligent than the Rosenbrock method and gives better convergence. A brief summary of the method and the source code for the program are given in Appendix B. The program moves all three thermocouples at a station until the error function is minimized. The error function is defined as the sum of absolute deviation of the temperatures from the linear temperature gradient through the condensation plate. This sum is added up for several sets of data at that station. All the data were analyzed using the IBM-3081D mainframe computer. For this optimization the data used were from Runs 13 through 33. The calculated displacements were then used to analyze all the steam condensation data for Runs 13 through 53. The results appear to be good, as discussed later in this chapter. The data for pure toluene condensation were also tested and found to be in good agreement with the anticipated results. The calculated displacement results are given in Table II and were used in all subsequent data analysis.

Data on Steam Condensation

The repetitive data reduction calculations involving condensing coefficients, local film Reynolds number, and local condensation number were performed using a computer program. The source code, the raw data and a set of sample calculations are given in Appendix C. The calculated heat transfer coefficients along with the predictions using the Nusselt equation are given in Table III. The plot of the local

TABLE II

THERMOCOUPLE DISPLACEMENTS (INCH)

Station	Front	Middle	Back
1	0.0160	0.0151	0.0123
2	0.0144	0.0144	-0.0013
3	0.0240	0.0335	-0.0113
4	0.0144	0.0229	0.0019
5	0.0323	0.0256	0.0008

TABLE III

STEAM CONDENSATION RESULTS

RUN	STATION 1		STATION 2		STATION 3		STATION 4		STATION 5	
	H	Q/A	H	Q/A	H	Q/A	H	Q/A	H	Q/A
13	3030	9920.	2010.	10400	1350	11200.	1220	11600	1110	13000
14	2680	9920	2070	10400	1360	11200.	1230	11600	1100	12900
15	2170	9820	2030	10400	1770	11700	1300	11700	1130	13000
16	2190	9820	1440	10300	1360	11500	1110	11600	1010	13000
17	2020.	9710	1600	10400	1290	11400	1100	11500	984	12900
18	1890	9640.	1410	10200.	1310	11400	1110	11500	1000	13000
19	2470.	9750.	2030	10300	1410	11300	1260	11500	777	12300
20	2330.	9690.	1980.	10300.	1560	11500	1260.	11500	1090	13000
21	2270	9790	1510.	10200.	1430.	11500.	1280	11700.	1060	13000
22	2420.	9840.	1560	10300	1470	11500	1250	11600	1090	13100
23	2250.	9730	1710	10300	1470	11400	1290	11700	1100.	13100
24	2470.	9580	1360.	9880	1390	11100	1220	11200	1100	12600
25	2200.	9520.	1470	9980	1260	11000	1160	11200	1080	12600
26	2180	9450	1480	9940	1330	11100	1150	11100	1060	12500
27	2210	9560	1470.	9980	1250	11100.	1100	11200	1030	12500
28	2400	9450	1290	9690	1180	10700	1190	11000	1010	12300
29	2470	9390	1380.	9710	1280	10800	1190	11000	1060	12300
30	2260.	9260	1390	9630.	1320	10800.	1210	11000	1070	12300
31	2420.	9410	1350	9670	1250.	10800	1210	10900	1120	12400
32	2320.	9390.	1400.	9710.	1300.	10800.	1240.	10900.	1140	12300
33	2290.	9390	1350	9650	1300.	10800.	1250	10900	1130	12300
34	2220.	9130.	1390.	9370.	1230.	10400	1130.	10600.	1100	12000
35	2190.	9040.	1510.	9420	1280.	10400.	1180.	10600.	1110	12000
36	1930.	8890.	1420.	9310.	1280.	10300.	1170.	10600.	1120.	12000.
37	2090.	9000.	1460.	9330	1240.	10300.	1090.	10600	1060.	11900
38	2160.	9020.	1370.	9310.	1210.	10300.	1090.	10500	1050.	11900
39	2350.	8270.	1330	8560	1190	9670.	1090	9930	1010	11300.
40	2140.	8120	1310.	8450.	1190.	9550.	1060	9910	1030	11300
41	2120.	8080.	1350.	8410	1270	9590.	1090	9890.	1030	11300.
42	2010.	7970.	1420	8410	1260	9510	1110.	9910	1070	11300
43	2280	8210	1520.	8520	1200	9570.	1110.	9860	1070	11300
44	2100	8040	1720.	8520	1300.	9590	1160.	9860	1090	11300

TABLE III (CONTINUED)

RUN	STATION 1		STATION 2		STATION 3		STATION 4		STATION 5	
	H	Q/A	H	Q/A	H	Q/A	H	Q/A	H	Q/A
45	2310	8460	1260	8600	1190	9670	1160	9910	1140	11300
46	2220	8290	1370	8580	1230.	9590	1180	9910	1180	11300
47	2940	6900.	1320	6900.	1200	7610.	1190	7820	1130	8720
48	2510	6660	1340.	6710	1320	7560.	1190	7710	1190	8700
49	2380.	6680	1440.	6840	1350.	7650	1180	7780	1170	8760
50	2580	7290	1890.	7550	1380.	8280	1260	8430	1220	9510
51	2370.	7130.	2050.	7490	1440	8220.	1280	8450	1230	9490
52	2300.	7140	2090.	7510	1480	8280	1300	8470	1230	9510

H · BTU/HR-SQ FT-DEGF (1 BTU/HR-SQ FT-DEGF = 5.68 W/SQ M-K)
Q/A · BTU/HR-SQ.FT (1 BTU/HR-SQ-FT = 3 155W/ SQ M)

condensation number against the local condensate Reynolds number is shown in Figure 8. The data match very well with the predictions of Nusselt theory. The slight scatter in the data at very low Reynolds numbers can be attributed to small amounts of dropwise condensation observed at the point of measurement during some of the runs. In previous work (18) it was observed that presence of non-condensibles such as air in the condensing vapor will dramatically affect the condensing coefficients and the heat fluxes. This problem appears to have been removed.

Data on Toluene Condensation

The data for toluene condensation were analyzed in the same manner as the steam condensation data. The source code, raw data and a set of sample calculations are included in Appendix D. The observed condensing coefficients and other results are presented in Table IV. The plot of the local condensation number against the local condensate Reynolds number is shown in Figure 9. The Reynolds numbers for toluene condensation are substantially higher than those observed for steam condensation. This is due to the much lower latent heat of condensation of toluene, resulting in higher mass flow rates. One distinct feature of the condensate flow patterns is the rippling effect observed. Still photographs were taken to record this phenomenon. Figure 10 and 11 show the condensate patterns for Run 69. Figures 12 and 13 are for Run 70. The rippling is expected to increase the condensing coefficients due to the turbulence it causes in the condensate film.

According to Dukler (16) the deviation from Nusselt theory can be correlated based on the Prandtl number of the condensate. The Prandtl

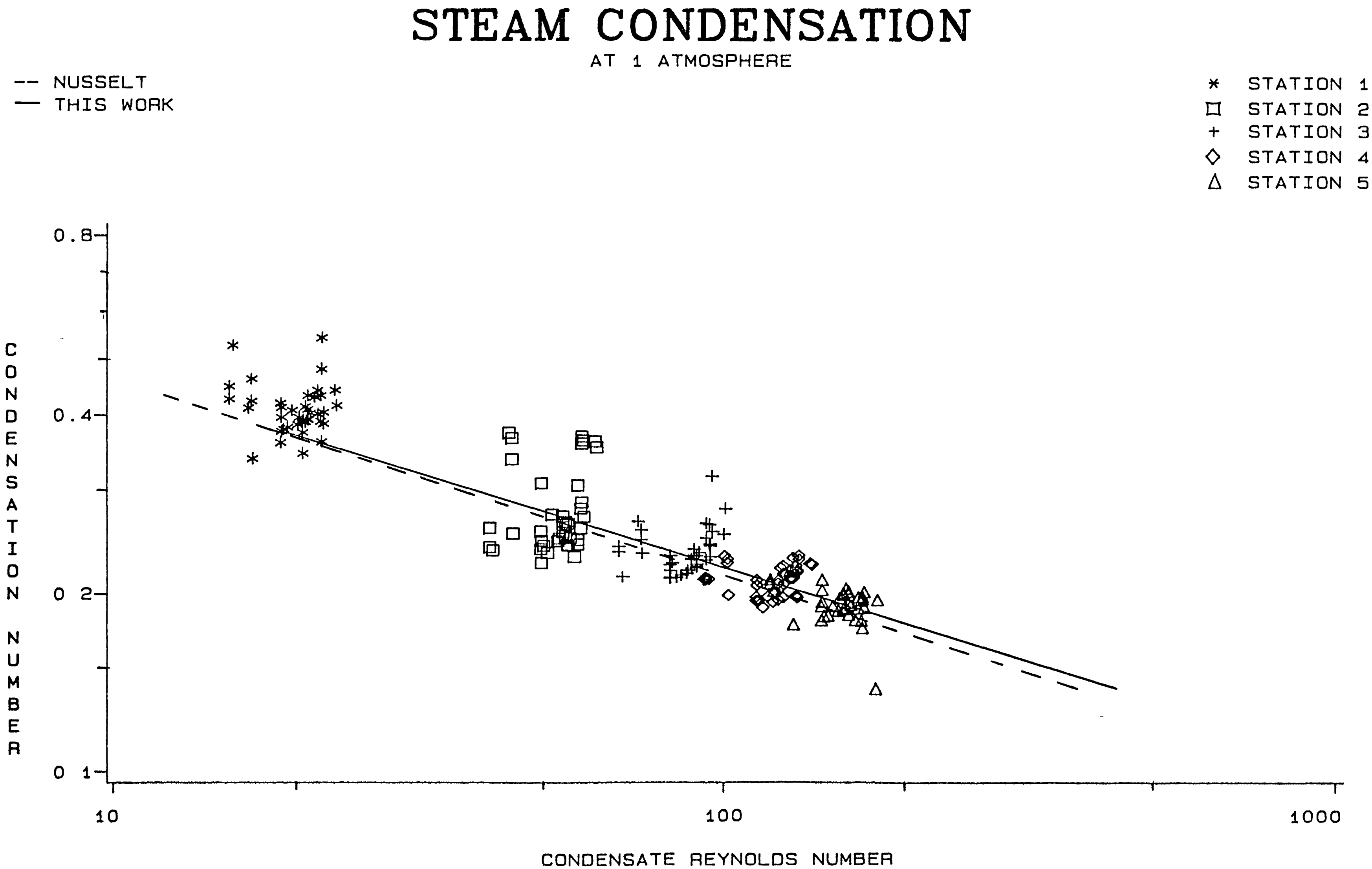

Figure 8. Steam Condensation Data and Correlation

TABLE IV

TOLUENE CONDENSATION RESULTS

RUN	STATION 1		STATION 2		STATION 3		STATION 4		STATION 5	
	H	Q/A	H	Q/A	H	Q/A	H	Q/A	H	Q/A
54	246	7820	204	7800	170	7670.	163	8050	161.	8820
55	246	7820	207	7830.	170.	7610	165.	8050.	163	8860
56	239	7690	209.	7760	173	7650	165.	8060	163	8840
57	248.	7930.	207	7910	171	7740.	166.	8160	160	8840
58	243	7860.	210.	7910	175.	7790	167	8140	164	8900
59	259	5460.	222.	5610.	196	5850	179	6110	173	6810
60	264.	5570	225	5710	194.	5910.	175	6090	172.	6830
61	294.	5160.	225.	5100	211	5540.	180	5540	127	4910
62	299	5140.	231	5100	215	5540.	181.	5460	178	6120
63	287.	4990	233	5060	221	5540.	198.	5540	180	6170
64	300.	5610.	221	5460	213	5960.	185.	5960.	179	6710
65	298	5460.	220	5330	213	5800	185.	5800	178	6390
66	297.	5050.	229.	5020	222.	5540.	187.	5480	182	6120
67	272.	8040	211.	7870	191.	8130.	175	8230.	168	8950
68	245.	4860.	216.	5040	207.	5540.	164.	5420.	134.	5640
69	251	7880.	208	7850.	188.	8090	166.	8060.	159	8740
70	285.	5290.	225.	5270	217.	5780	183	5710	180	6470
71	276	8100.	210.	7870.	191.	8130.	175.	8250	166	8960.
72	271.	7160.	213.	7130	194	7560.	176	7780	172	8720
73	279.	6900.	219.	6820.	195.	7220.	176.	7490.	174.	8480.

H : BTU/HR-SQ.FT-DEGF (1 BTU/HR-SQ FT-DEGF = 5 68 W/SQ M-K)
Q/A . BTU/HR-SQ.FT (1 BTU/HR-SQ-FT = 3.155W/ SQ.M)

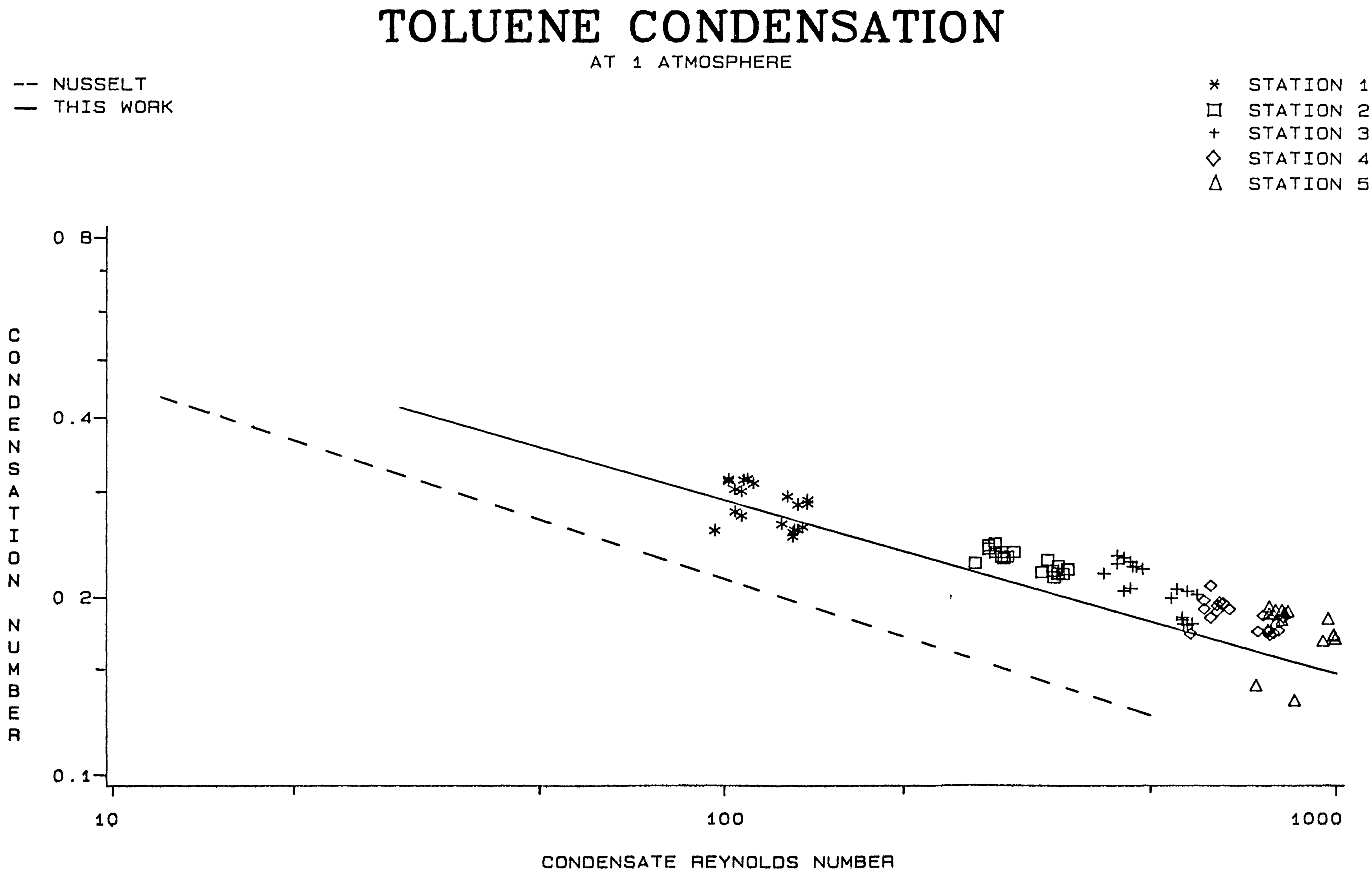

Figure 9. Toluene Condensation Data and Correlation

Figure 10. Toluene Condensate - Wavy Flow 1

Figure 11. Toluene Condensate - Wavy Flow 2

Figure 12. Toluene Condensate - Wavy Flow 3

Figure 13. Toluene Condensate - Wavy Flow 4

number for toluene condensate is more than twice that for water. And this could explain the deviation from the Nusselt theory. Quantitative comparison with Dukler's result was not done because his results are presented for condensate Reynolds numbers well above 100 whereas the data obtained in this work are for Reynolds numbers ranging to as low as 20. A qualitative extrapolation of Dukler's results yields condensing coefficients similar to those observed in this work. As will be seen later, another substance with much higher condensate Prandtl number was studied and much more rippling was observed. Also the condensing coefficients showed a greater deviation from the Nusselt theory. There was no method available to quantify the intensity and velocity of the waves observed for these two substances. Possible explanations and correlations are given later in this chapter.

Data on Toluene-Water Mixture

Toluene and water form an eutectic mixture at atmospheric pressure with a composition of 44.3 mole% (82.5 wt%) toluene and 55.7 mole% water. The corresponding eutectic temperature is 184°F. The data obtained on toluene-water mixture condensation agree well with the eutectic composition.

The toluene-water mixture condensation data were analyzed using another computer program. The calculations involved local condensing coefficients, local film Reynolds numbers, and local condensation numbers. The source code, raw data and a set of sample calculations are given in Appendix E. The condensing coefficients and other results are presented in Table V. As expected, the condensing coefficients are in between those observed for the two pure components. This has led to

TABLE V

TOLUENE-WATER CONDENSATION RESULTS

RUN	STATION 1 H	STATION 1 Q/A	STATION 2 H	STATION 2 Q/A	STATION 3 H	STATION 3 Q/A	STATION 4 H	STATION 4 Q/A	STATION 5 H	STATION 5 Q/A
75	431	7760	391	8100	401.	8940	403	9360	371	10200
76	559.	7630	453	7870	346	8000	381	8540	397.	9640
77	576	8400	473	8500	397	8800	394	9050	375	9840
78	565	8910	476	9000	362	8940	397	9400	393.	10100
79	640	7500.	397	7200	381	7420	420	7730	386	8310
80	586.	7710.	412	7490	384	7680	425	7960	366	8430
81	588	7840	459	7720	410	7990.	360	7760	341	8340
82	653	7430	437	7260	364	7320	399	7630	341	8170
83	610	7780	435.	7640	380	7690	377	7760	355	8460
84	613.	7910	397.	7580	397	7850	380	7780	366	8490
85	606.	6810	391	6650	390	6980.	390	7190	362	7890
86	590	7110	417	7030	407	7330.	358	7230	346	7950
87	585.	7050.	434.	7070.	396.	7260	358.	7290.	336	7910
88	590.	7540	420.	7430	414	7750	382.	7670	332	8130
89	608.	7710	398	7430	382.	7620	376.	7730	334	8250
90	560.	7800.	408.	7640	371.	7700.	360.	7780	301	8030
91	583.	7260	405	7130	373	7420	383	7650	338	8270
92	532	7690.	414.	7640	354.	7740.	384.	7970.	339	8520
93	613.	7710.	441.	7590.	351.	7660.	368	7990	355	8880
94	574.	7990.	412.	7890.	347	7990.	405.	8490	337	8980
95	553.	8440.	432.	8410	364.	8450	365	8520	352	9270
96	607.	9300	421	8890	125	4760	354	8910	321	9470
97	593.	9000.	407.	8640.	122.	4530.	357	8830	328	9490
98	596.	8940.	459.	8750	126	4660	328	8660	329	9530
99	539.	8210.	458.	8390	123	4420.	345	8580	335	9410
100	534.	8960.	418.	8890	128.	4770	338	8980	301	9350
101	550.	7610	415	7680	377	8180	382	8410.	314	8990
102	558	8380.	469	8500	372	8610	381.	8790	331	9450
103	551	8980	429	8850	410	9280	346	8920	318	9550
104	661	5050	474	5080	417.	5440	387	5480	354	6120
105	612.	4180	533	4390	421	4790.	355	4570	341	5130
106	603.	4610.	493.	4960	476	5500	351	5460	352	6300

TABLE V (CONTINUED)

RUN	STATION 1 H	STATION 1 Q/A	STATION 2 H	STATION 2 Q/A	STATION 3 H	STATION 3 Q/A	STATION 4 H	STATION 4 Q/A	STATION 5 H	STATION 5 Q/A
107	670.	5180	487	5310	390	5740	386	6030	363	6910
108	559	4480.	459	4790	407	5270	369	5370	313	5980
109	528.	3960	468	4390	420	4890	378	4970	353	5700
110	652.	5930.	427	5960	391	6260	376	6410	338	7140
111	583.	5590	442	5730	364	5950	396	6220	331	6830
112	579	5310.	497.	5560	376.	5850	357	5960	328	6610
113	549.	4670.	473	4960.	397	5290	370	5290	307	5720
114	649.	7370	473	7490.	375	7520.	383	7950	351	8840
115	562.	8440.	458.	8660.	352.	8930.	348	8830	353	9960
116	607.	9210	446	9190	358	9210	370	9600	342	10400

H · BTU/HR-SQ.FT-DEGF (1 BTU/HR-SQ.FT-DEGF = 5.68 W/SQ.M-K)
Q/A : BTU/HR-SQ FT (1 BTU/HR-SQ-FT = 3 155W/ SQ M)

many correlation using some sort of weighted average for the mixture condensing coefficients. The most successful efforts are those of Bernhardt et al. (7). The predictions of the Akers and Turner (1) correlations do not agree well with the data. Another approach presented later in this chapter is used in this work to correlate the data.

Several still photographs were taken and are presented here. Figures 14 through 18 are for Run 91 at Stations 1 through 5, respectively. Figures 19 through 23 are for Run 98 at Stations 1 through 5, respectively. The heat fluxes and condensing coefficients are given in Table V. Due to one bad thermocouple reading in Runs 96 through 100 at Station 3, the heat flux and condensing coefficient calculated are obviously incorrect. Motion picture sequences were also obtained to study the condensate flow patterns. The film was made for Run 116. Contrary to the popular conception, there are several types of condensation patterns visible at any location at different times, under the same process conditions. There are no sharp boundaries separating the condensate flow patterns. At Stations 1 and 2 the film-drop-rivulet pattern is dominant and some standing drops are also seen. The drops are large in size at these stations as compared to those at Stations 4 and 5. The condensate film velocity appears to be substantially higher at Stations 4 and 5. The water drops underneath the film are deformed due to the shear caused by the film.

Data on R-113 Condensation

In order to study an extreme case in terms of mixture composition, R-113 (112 triflouro 112 trichloro-ethane) was chosen. The data for

Figure 14. Toluene-Water Condensate
- Run 91, Station 1

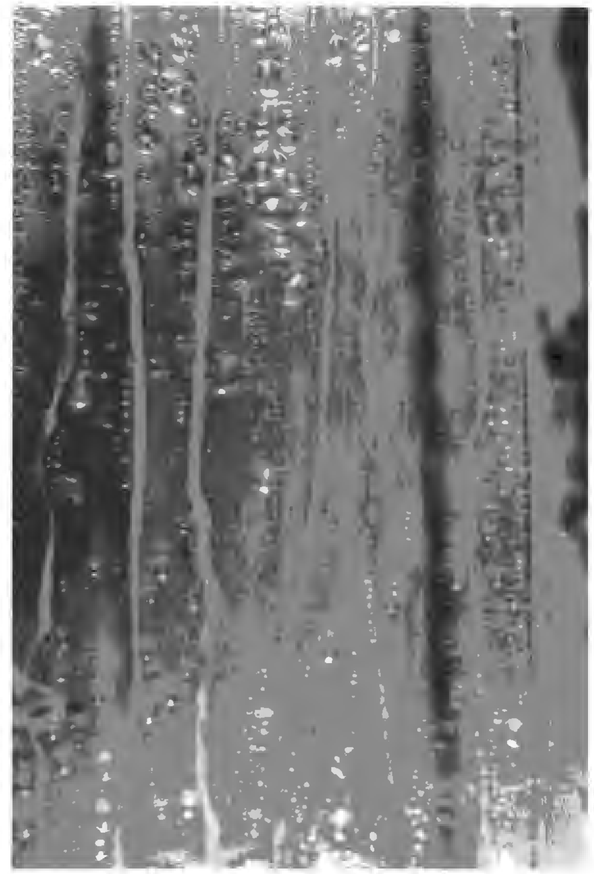

Figure 15. Toluene-Water Condensate
- Run 91, Station 2

Figure 16. Toluene-Water Condensate - Run 91, Station 3

Figure 17. Toluene-Water Condensate - Run 91, Station 4

Figure 18. Toluene-Water Condensate - Run 91, Station 5

Figure 19. Toluene-Water Condensate - Run 98, Station 1

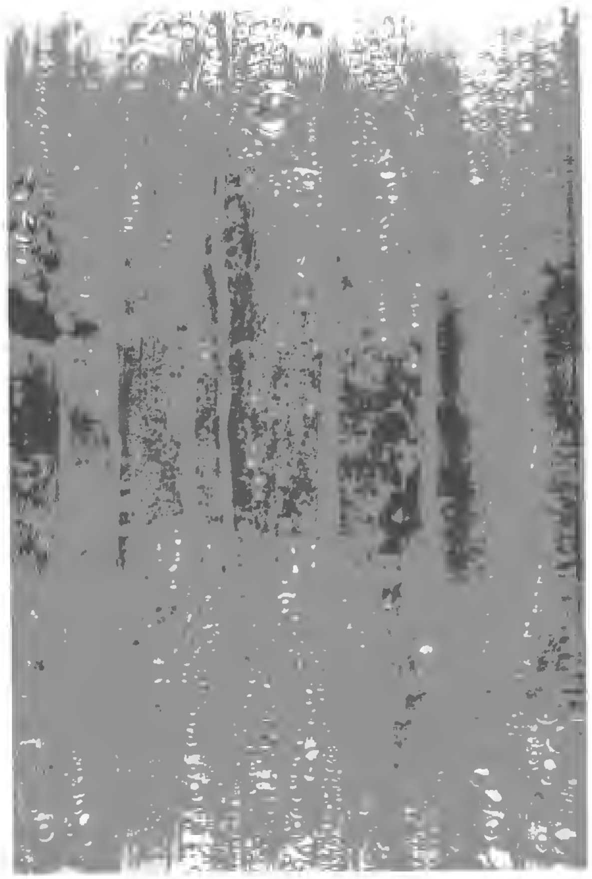

Figure 20. Toluene-Water Condensate - Run 98, Station 2

Figure 21. Toluene-Water Condensate - Run 98, Station 3

Figure 22. Toluene-Water Condensate - Run 98, Station 4

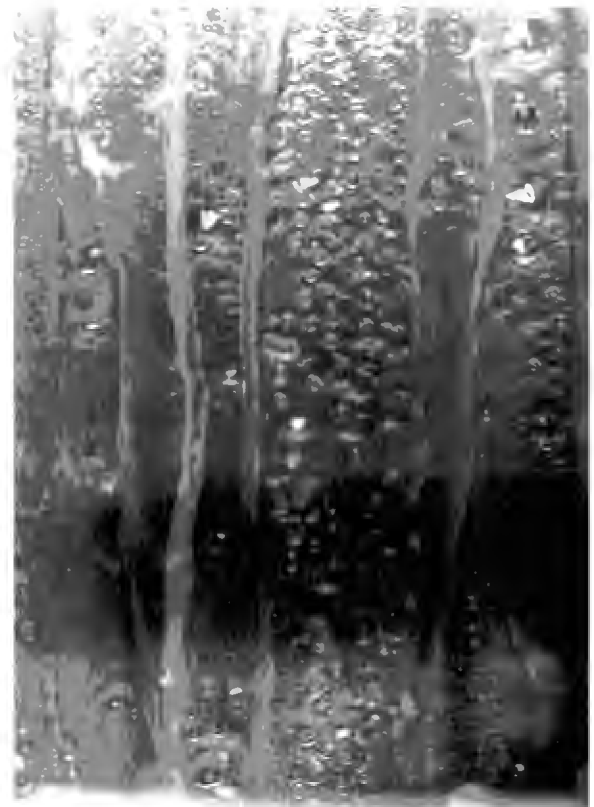

Figure 23. Toluene-Water Condensate - Run 98, Station 5

pure R-113 were analyzed using a computer program similar to that used for pure toluene except for the properties. The source code, the raw data and a set of sample calculations are given in Appendix F. The condensing coefficients observed and other results are presented in Table VI. A plot of the local condensation number against the local condensate Reynolds number is shown in Figure 24. The data range from Reynolds numbers of about 20 to about 300. At the lower end of this range, the condensation numbers show some deviations from the Nusselt theory prediction. At higher Reynolds numbers the condensation numbers are much higher than those predicted using Nusselt theory. The condensate Prandtl number for R-113 is substantially higher than that for steam and according to Dukler (16) this accounts for the higher condensing coefficients.

The condensate showed a substantial amount of rippling. The waves were much higher in number and faster moving than those seen for pure toluene condensation. Figures 25 through 29 were obtained at Stations 1 through 5, respectively for Run 132. Moving from Station 1 toward Station 5, a distinct increase in the frequency of waves is seen. The turbulence in the condensate film can be attributed to the waves, resulting in higher condensing coefficients.

Data on R-113-Water Mixture

R-113 and water form an eutectic mixture at atmospheric pressure with a composition of 90.7 mole% (98.3 wt%) R-113 and 9.3 mole% water. The corresponding eutectic temperature is 113°F.

The R-113-water eutectic mixture contains very small amounts of water. This is due to the much larger vapor pressure of the R-113 at

TABLE VI

R-113 CONDENSATION RESULTS

RUN	STATION 1 H	STATION 1 Q/A	STATION 2 H	STATION 2 Q/A	STATION 3 H	STATION 3 Q/A	STATION 4 H	STATION 4 Q/A	STATION 5 H	STATION 5 Q/A
117	194	2980	165	2930	154	2970	132	2820	131	3040
118	185.	2950	170	2990	152	2990.	132	2870	129	3080
119	190	3000	170	2990	149.	2970.	133	2870	124	3020
120	190	3060	176.	3090	154	3090	133	2950	129	3160
121	195.	2870.	173	2880	146	2830	131	2780	120	2880
122	189	2830	172	2860	150	2850	132.	2800	128	3020
123	214	3250	170.	3090.	148	3050	137	3010.	128	3140.
124	197	2800.	175	2840	153	2850	136	2840	129	3040
125	203.	2890.	182	2950	156	2950	140	2950	132	3160
126	214.	2830.	174.	2780	154	2790.	140.	2820	132.	3000.
127	194.	2650.	173.	2700	152.	2730	133.	2700	127.	2900
128	181.	2550.	177.	2700.	151	2710	127.	2650.	121	2840
129	224.	1800.	187.	1770	170.	1810	146	1770.	144	1900
130	211.	1690	194.	1730	176	1790.	146	1700	143	1860
131	190	1580.	193.	1710.	182.	1810.	144	1710	144.	1880
132	202.	2720.	168	2700.	150	2730.	137.	2760	127	2920

H : BTU/HR-SQ.FT-DEGF (1 BTU/HR-SQ.FT-DEGF = 5 68 W/SQ.M-K)
Q/A : BTU/HR-SQ.FT (1 BTU/HR-SQ-FT = 3.155W/ SQ.M)

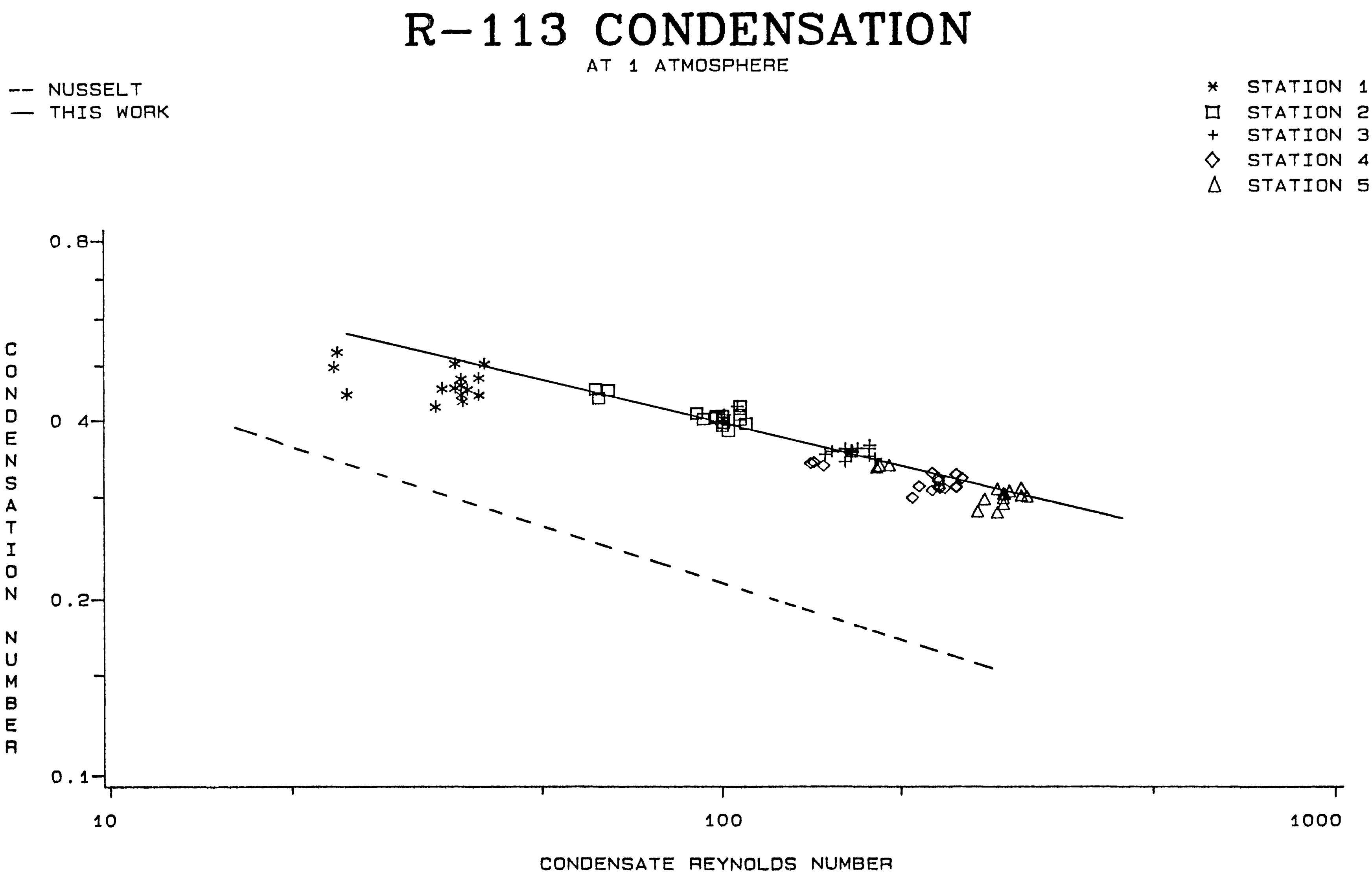

Figure 24. R-113 Condensation Data and Correlation

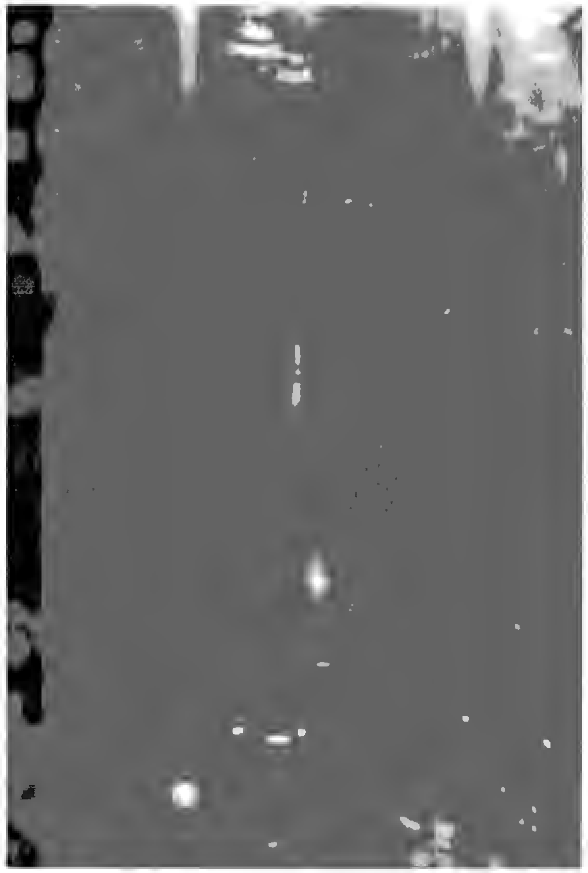

Figure 25. R-113 Condensate - Run 132, Station 1

Figure 26. R-113 Condensate - Run 132, Station 2

Figure 27. R-113 Condensate, Run 132, Station 3

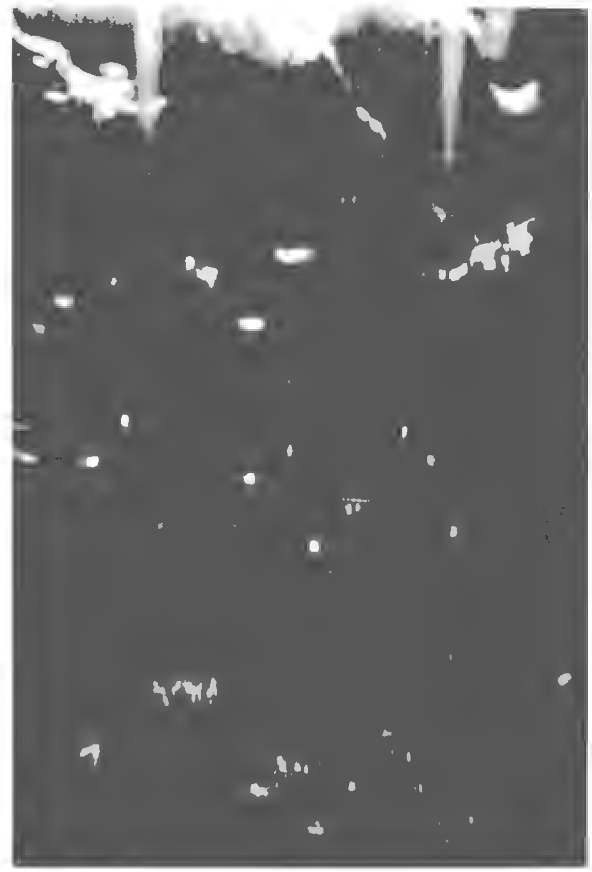

Figure 28. R-113 Condensate - Run 132, Station 4

Figure 29. R-113 Condensate - Run 132, Station 5

the eutectic temperature. This makes the study of this mixture unique. The data were analyzed using a computer program similar to the one used for the toluene-water mixture. The source code, raw data and a set of sample calculations are included in Appendix G. The condensing coefficients and other results are given in Table VII. The condensing coefficients show trends similar to those for pure R-113 condensation. Due to very small amounts of water, it is not possible to see any distinct increases in the mixture condensing coefficients.

Figures 30 through 34 were taken for Run 145 at Stations 1 through 5, respectively. Station 1 showed a distinct film-standing drop pattern. The waves appear to be present at Station 2 and continue to increase in density and velocity towards Station 5. The density of the drops is gradually reduced. At Station 5 there are almost no standing drops observed. Figures 35 through 39 are for Run 146 at Stations 1 through 5, respectively. These appear similar to Figures 30 through 34 except the one at Station 5. The amount of standing drops seen in Figure 39 is much more than in Figure 34.

Condensate Flow Mechanism Models

Three types of flow modes may be envisioned to describe the condensate flow mechanisms. The first is a two film model as described by Sykes and Marchello (43). According to this model, the organic liquid forms a continuous film on the condensation surface. The aqueous phase forms another film, on top of the organic film. The major difficulty of this model is the transport of the organic component from the vapor phase to the organic film, across the aqueous film. No explanation appears to be satisfactory. Sykes and Marchello (43)

TABLE VII

R-113-WATER CONDENSATION RESULTS

RUN	STATION 1		STATION 2		STATION 3		STATION 4		STATION 5	
	H	Q/A	H	Q/A	H	Q/A	H	Q/A	H	Q/A
133	238.	2800.	169	2630.	153	2650	139	2610	144	2860
134	216.	2680.	153	2420	150.	2610	129	2510	130	2700
135	214.	2630.	168	2590	156	2650	131	2530	135	2760
136	243	2910.	177.	2780	151.	2750	135	2700	127	2840
137	240.	2870	180	2780	155	2770	131	2660.	126	2830
138	235.	2760	183.	2740	164	2770	134	2630	133	2880
139	248	2830	168.	2590	150.	2610.	138	2590	133	2740
140	247	2740.	182.	2630	160.	2650.	134	2530	133	2740
141	229.	2630	192.	2680.	159	2650.	122	2360	135	2780
142	261	1770.	195	1690.	173	1730.	150.	1680.	141	1780.
143	241.	1650	209	1670.	186	1750.	143.	1620	145	1780.
144	226.	1560.	215.	1670.	188	1730.	139	1580	132	1680
145	254.	2720.	169.	2510.	147.	2510.	134.	2530	128.	2670
146	241.	2570.	186.	2550.	164.	2610	136.	2550	132.	2760
147	218.	2480.	191.	2590.	165.	2630.	134	2530	130	2740.
148	263.	2760.	169.	2490	153	2490.	134.	2420.	128	2510.

H : BTU/HR-SQ.FT-DEGF (1 BTU/HR-SQ.FT-DEGF = 5.68 W/SQ.M-K)
Q/A : BTU/HR-SQ.FT (1 BTU/HR-SQ-FT = 3 155W/ SQ M)

Figure 30. R-113-Water Condensate
- Run 145, Station 1

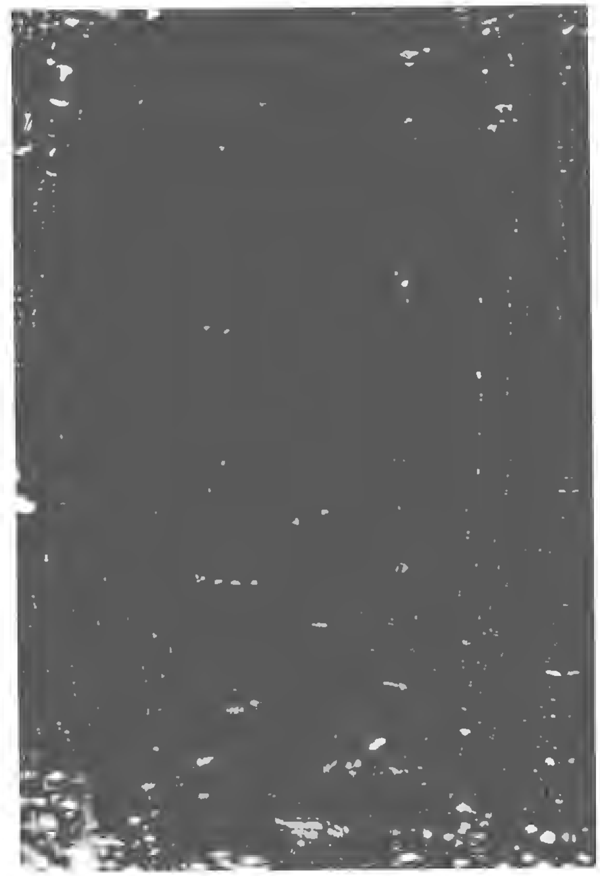

Figure 31. R-113-Water Condensate
- Run 145, Station 2

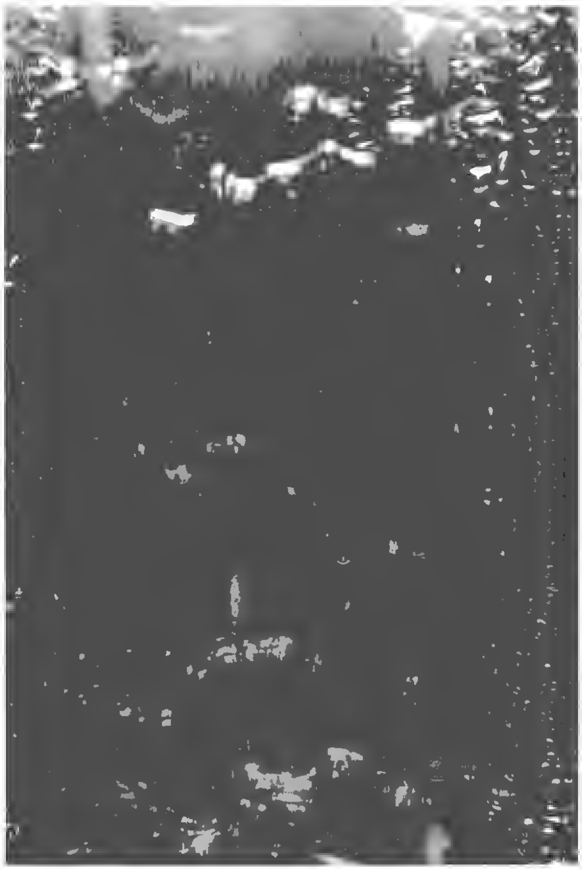

Figure 32. R-113-Water Condensate - Run 145, Station 3

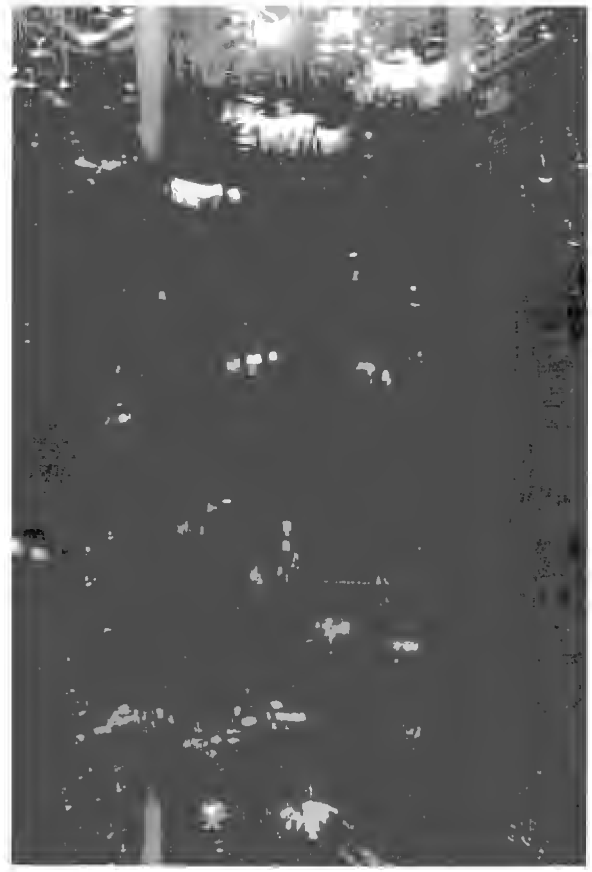

Figure 33. R-113-Water Condensate - Run 145, Station 4

Figure 34. R-113-Water Condensate - Run 145, Station 5

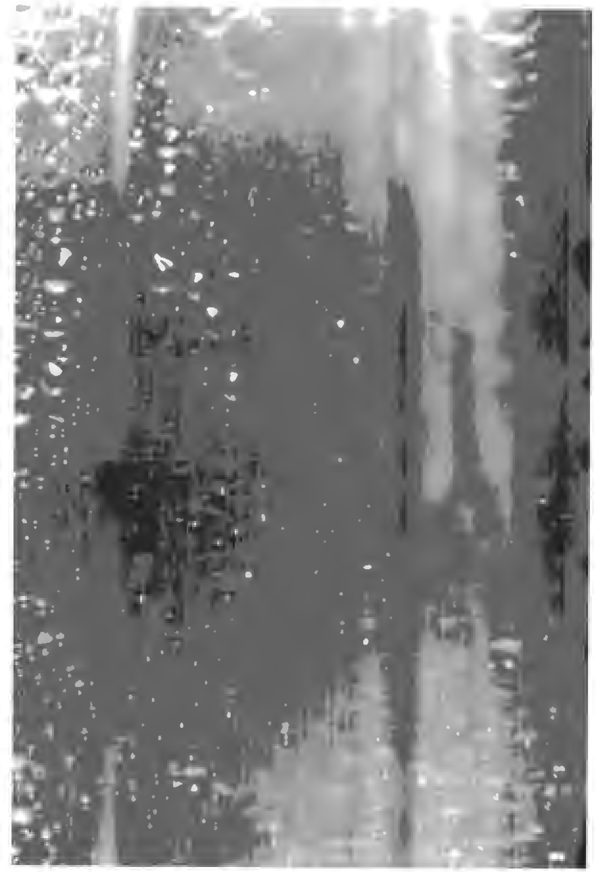

Figure 35. R-113-Water Condensate - Run 146, Station 1

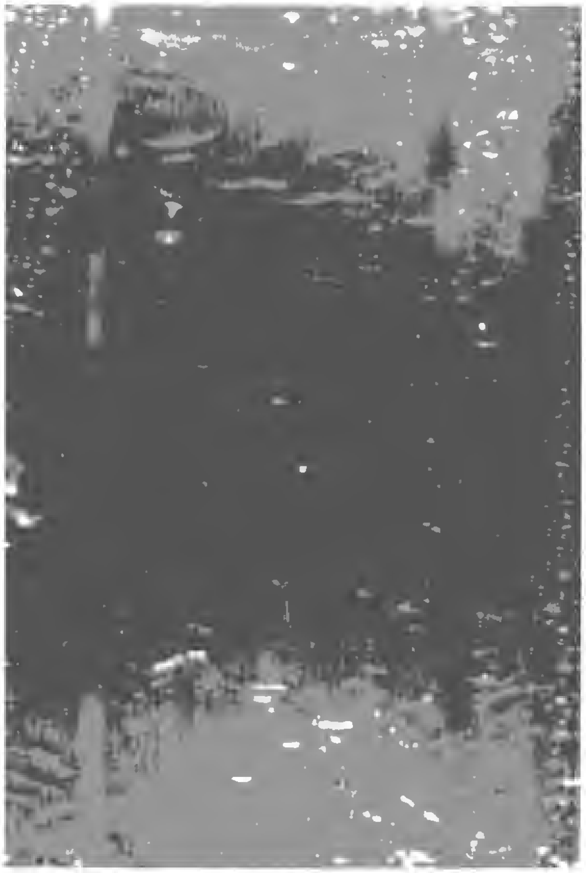

Figure 36. R-113-Water Condensate - Run 146, Station 2

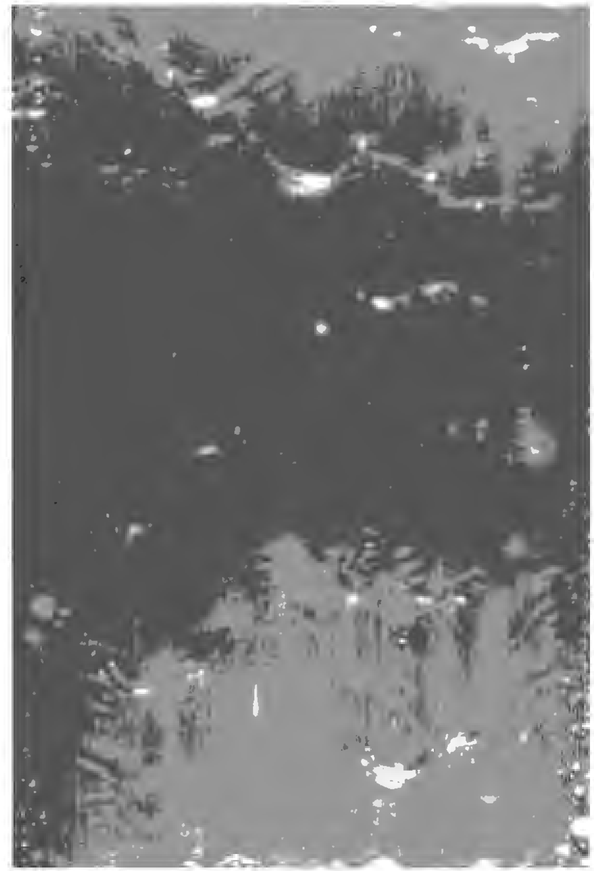

Figure 37. R-113-Water Condensate - Run 146, Station 3

Figure 38. R-113-Water Condensation - Run 146, Station 4

Figure 39. R-113-Water Condensate - Run 146, Station 5

assumed an instantaneous transport of the condensed organic liquid across the water layer. The heat transfer occurs across two resistances in series. The effective thermal conductivity and film thickness calculations are performed by Sykes and Marchello. However, their results do not agree with their data.

The second model is applicable to any flow mechanism that assumes the two phases condensing without any interaction. This means that the water and organic vapors condense at different locations on the surface. This is depicted in the double dropwise and the channeling flow models of Hazelton and Baker (20). The two liquid phases in essence share the condensation surface. The heat transfer can be assumed to take place across the aqueous and the organic liquids independently of each other. The heat transfer area may then be divided in proportion to the surface occupied by each phase. If the area division is assumed to be proportional to the condensate volumes, the aqueous and the organic condensing coefficients can be averaged based on the condensate volume fraction of each phase. This leads to the following correlation proposed by Bernhardt et al. (7).

$$h = \frac{h_o\, v_o + h_w\, v_w}{v_o + v_w} \qquad (5.1)$$

If the film thicknesses of the two phases are different and are taken into account in averaging the condensing coefficients, other forms of the above equation are possible.

The third model assumes the organic phase to be flowing in the form of a film. The aqueous phase forms drops on the condensation surface in a random fashion and flows from the drops. The organic phase flows in the form of film, over and around the water drops. Some of the water drops may be exposed to the vapor phase. The condensation occurs at the vapor-liquid interface. The water condensed on the organic film forms small droplets and due to the dynamic nature of the organic condensate film, moves freely in the film. The droplet size varies and is usually considerably smaller than the organic film thickness. When the small water droplets come in contact with a standing drop of water, the two coalesce and the standing drop grows. Under the forces of gravity and shear of the organic film, the larger standing drops detach from the condensation surface and flow as drops or rivulets. They may carry small droplets of the organic phase with them. These organic droplets are formed by the condensation of the organic vapor on the water drops exposed to the vapor. When the water drops drain, they leave a residual water film on the condensation surface and the growth of new standing drops is promoted at these sites.

The model in essence depicts relatively well mixed organic and water phases. This pseudo-emulsion type condensate may be considered similar in behavior to a homogeneous mixture. Hence assuming a homogeneous mixture, the properties of the condensate may be evaluated. With these, the data can then be correlated in a manner similar to the single component condensation.

The observed condensate flow patterns for mixture condensation most closely resembled the third model and the homogeneous mixture approach was used to correlate the data. Several methods are reported in the literature (37) to average the various properties of homogeneous mixtures. These range from very simple to very exotic relationships. Heat transfer across the condensate is essentially conductive in the loading range studied. Hence, the thermal conductivity of the condensate is the most important physical property under consideration. If the thermal conductivity of a mixture is weight averaged, the maximum estimation error is reported to be less than 4% by Reid et al. (37) for completely miscible mixtures. For other properties, the following averaging equations are used:

$$C_{pl} = (C_{P_o} W_o + C_{P_w} W_w)/(W_o + W_w) \tag{5.2}$$

$$\mu_l = \frac{W_o + W_w}{\dfrac{W_o}{\mu_o} + \dfrac{W_w}{\mu_w}} \tag{5.3}$$

$$\rho_l = (\rho_{lo} V_o + \rho_{l_w} V_w)/(V_o + V_w) \tag{5.4}$$

$$\rho_v = \frac{W_w + W_o}{\dfrac{W_w}{\rho_{vw}} + \dfrac{W_o}{\rho_{vo}}} \tag{5.5}$$

The local condensate Reynolds number and the local condensation number for the two mixtures were calculated using the averaged properties. The equations used are as below.

$$N_{co_x} = h_x \left[\frac{k_l^3 \rho_l^2 g}{\mu_l^2}\right]^{-1/3} \tag{5.6}$$

$$Re_x = \frac{4 (W_{o_x} + W_{w_x})}{(\text{surface width}) \mu_l} \tag{5.7}$$

These are plotted in Figures 40 and 41. Using some other averaging method for all the properties except the liquid thermal conductivity

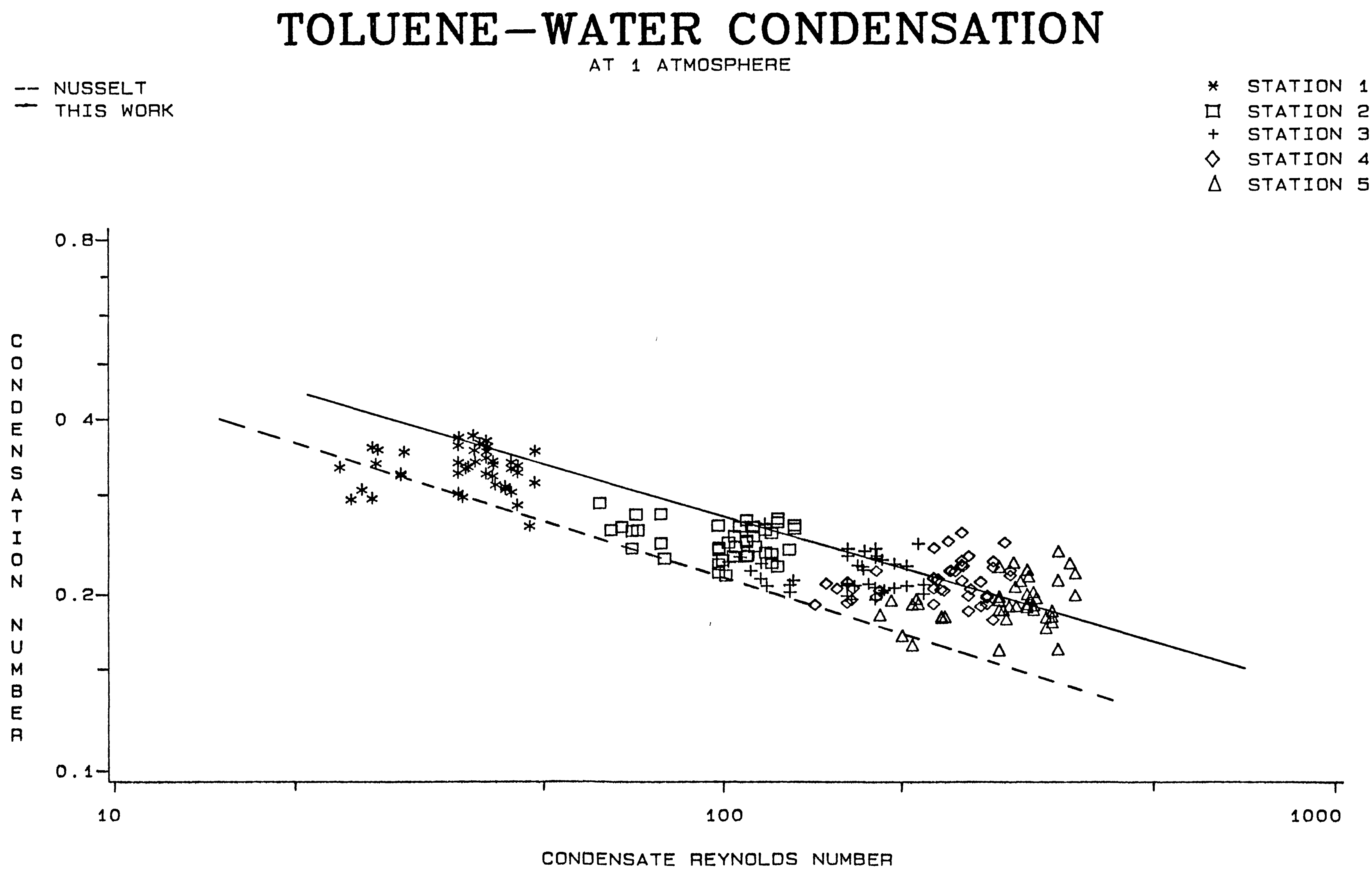

Figure 40. Toluene-Water Condensation Data and Correlation

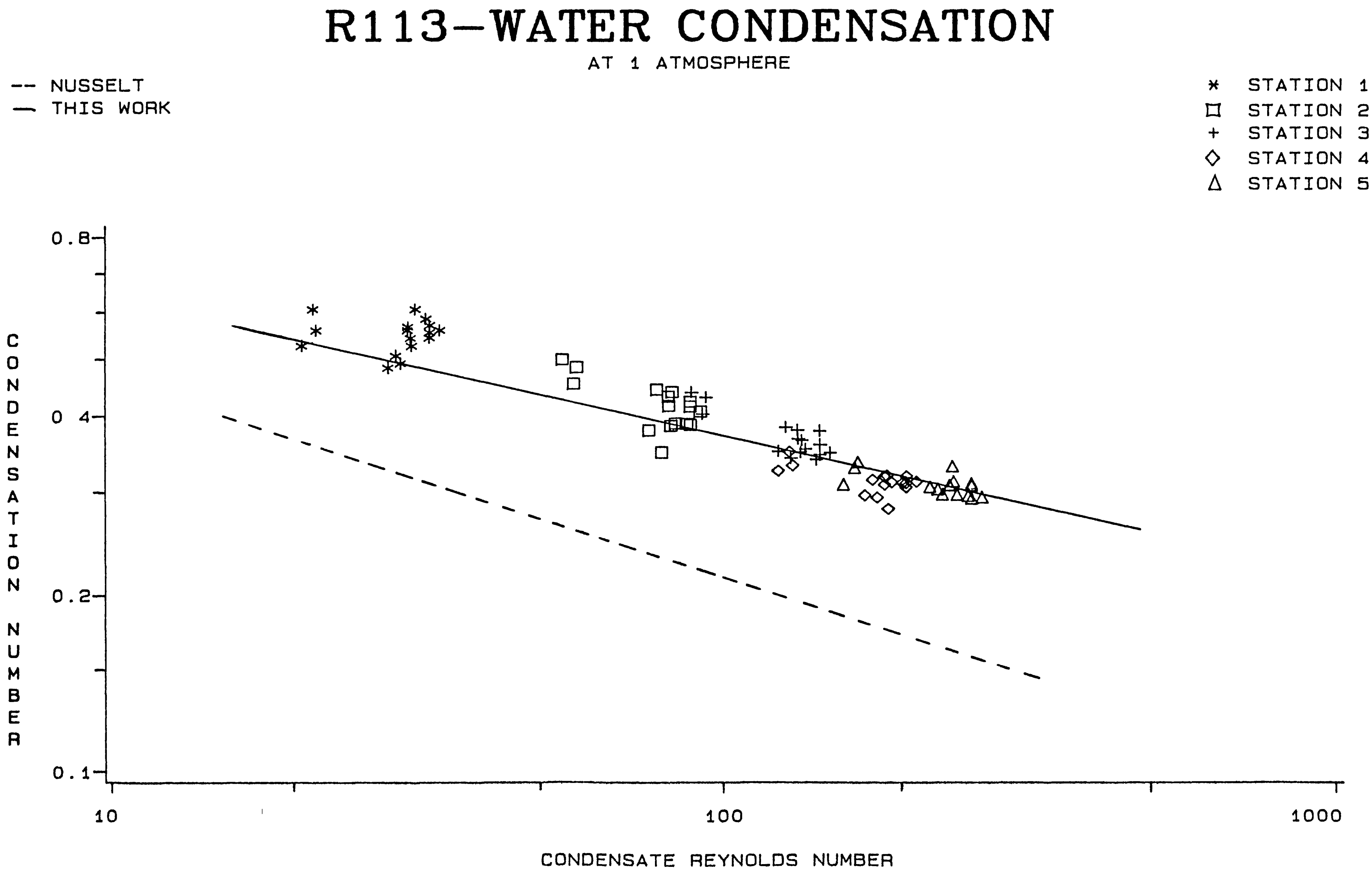

Figure 41. R-113-Water Condensation Data and Correlation

does not make a significant difference in the plots in Figures 40 and 41.

For the toluene-water mixture the Reynolds number range covered is intermediate between those for pure toluene and pure steam. The data appear to lie in a straight line. The slope is this line is intermediate between that for pure toluene and pure steam. The condensate Prandtl number for toluene-water mixture is also intermediate between that for pure toluene and pure water. This accounts for the difference in the slopes of the straight lines drawn through these data. The condensing coefficients for toluene-water mixture appear to deviate from the straight line around the Reynolds number of 250. In this region, the condensate flow patterns also showed significant numbers of large drops on the condensing surface. The pseudo-homogeneous flow model described above is not applicable to condensation with enhanced separation of the two phases. The volume averaging of condensing coefficients as described in the second model above would be more applicable. These data for Reynolds numbers above 250 appear to be in a transition regime between the two models. More data are needed for higher Reynolds numbers to properly test the shared surface mechanism in the second model.

The properties of the R-113 and water mixture are very close to those of pure R-113 due to the very small amount of water present in the eutectic mixture. A plot of the local condensation number versus local condensate Reynolds number in Figure 41 shows the same trends as Figure 24 for pure R-113 condensation. A small fraction of the data obtained are for condensate Reynolds numbers above 250. For Reynolds numbers above 250 there appears to be a small deviation from the straight line. This deviation is very small compared to that seen in the toluene-water mixture data. Figures 34 and 39 are taken at Station 5 for Runs 145 and 146, respectively. In Figure 34 the density of large standing drops is quite small compared to Figure 39. Figure 39 in turn, has few large standing drops as compared to the toluene-water mixture. The condensate flow patterns for R-113-water mixture appear to behave as described in the third model instead of the second model even for Reynolds numbers above 250. The primary reason could be the relatively very small amount of water present in the mixture. Again, more data are needed for Reynolds numbers well above 250 to study the flow mechanism in the transition regime and the shared surface model.

Correlation and Prediction Method

To correlate all the data together, an equation of the type below is best suitable.

$$N_{co_x} = a\ Re_x^{\ b} \tag{5.8}$$

The values of a and b can be estimated with the following relationships. These relationships were derived using the experimental data.

$$a = 0.208 \log_{10} \overline{Pr} + 1.02 \tag{5.9}$$

$$b = 0.127 \log_{10} Pr - 0.367 \tag{5.10}$$

In order to estimate a condensing coefficient for a single component or an immiscible mixture, the following procedure can be used.

1. For an immiscible mixture, the condensate properties must be evaluated assuming homogeneous mixture. Equations 5.2 through 5.5 can be used for this purpose.

2. Calculate the condensate Prandtl number.

3. Using Equations 5.9 and 5.10 above, calculate a and b.

4. Estimate the condensate Reynolds number at the location on the condensing surface for which the condensing coefficient is to be calculated.

5. Using Equation 5.8, calculate the condensation number.

6. Using the properties of the condensate, calculate the condensing coefficient.

7. If an average value of the condensing coefficient is needed for the length of the surface, then the local condensing coefficients calculated must be integrated along the length of the surface.

Comparison between predicted and experimental data was done and the results are plotted in Figures 42 through 46. For the case of toluene condensation, the experimental values are higher than predictions. The toluene data are for relatively high condensate Reynolds numbers. The effect of high condensate Reynolds numbers is not fully accounted for in the prediction method. Hence, some deviation shows up between the predicted and experimental values.

The prediction method described above can be safely used for single components as well as mixtures with condensate Prandtl numbers between 1 and 10 and condensate Reynolds numbers below 1000. However, due to the

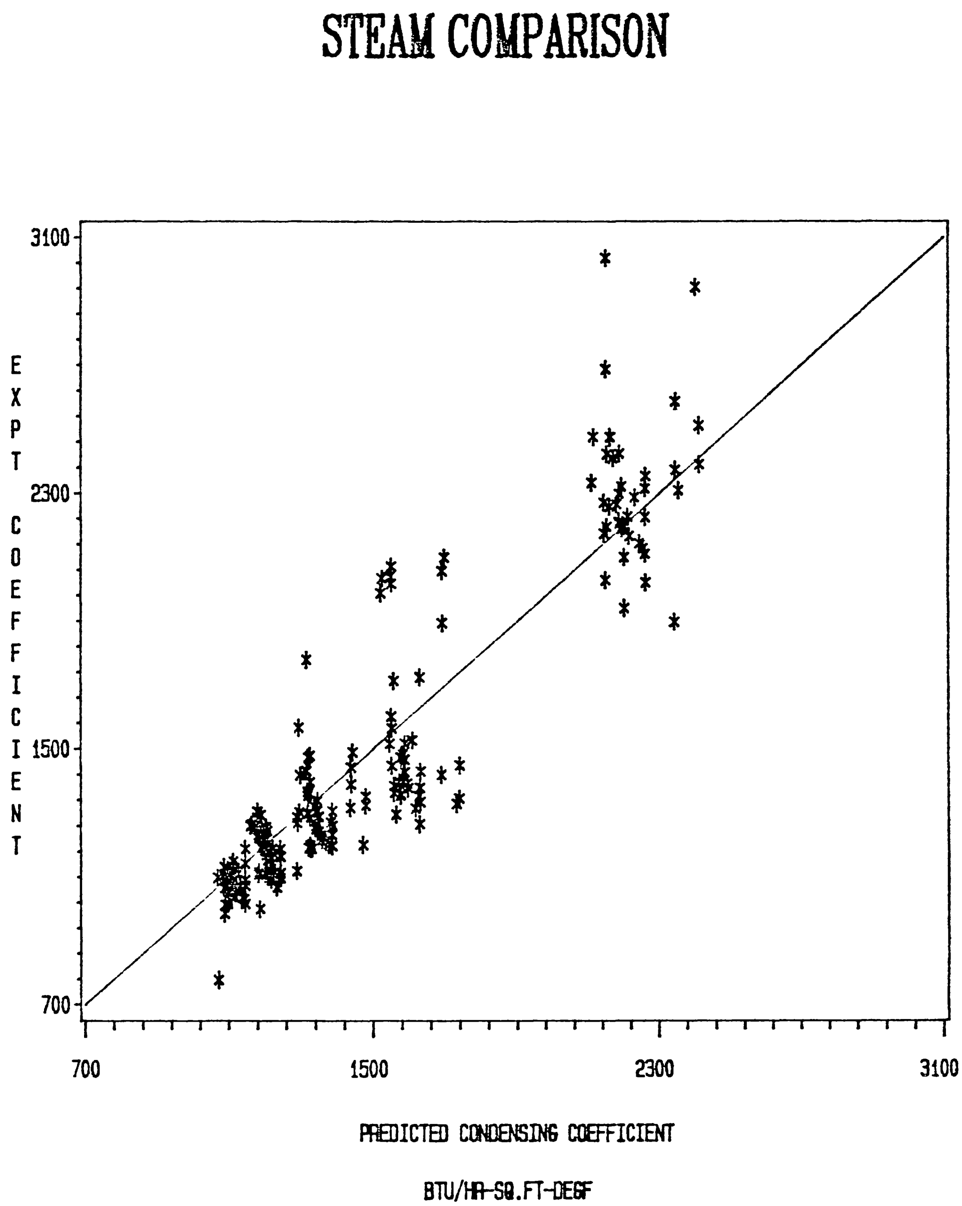

Figure 42. Steam Comparison

TOLUENE COMPARISON

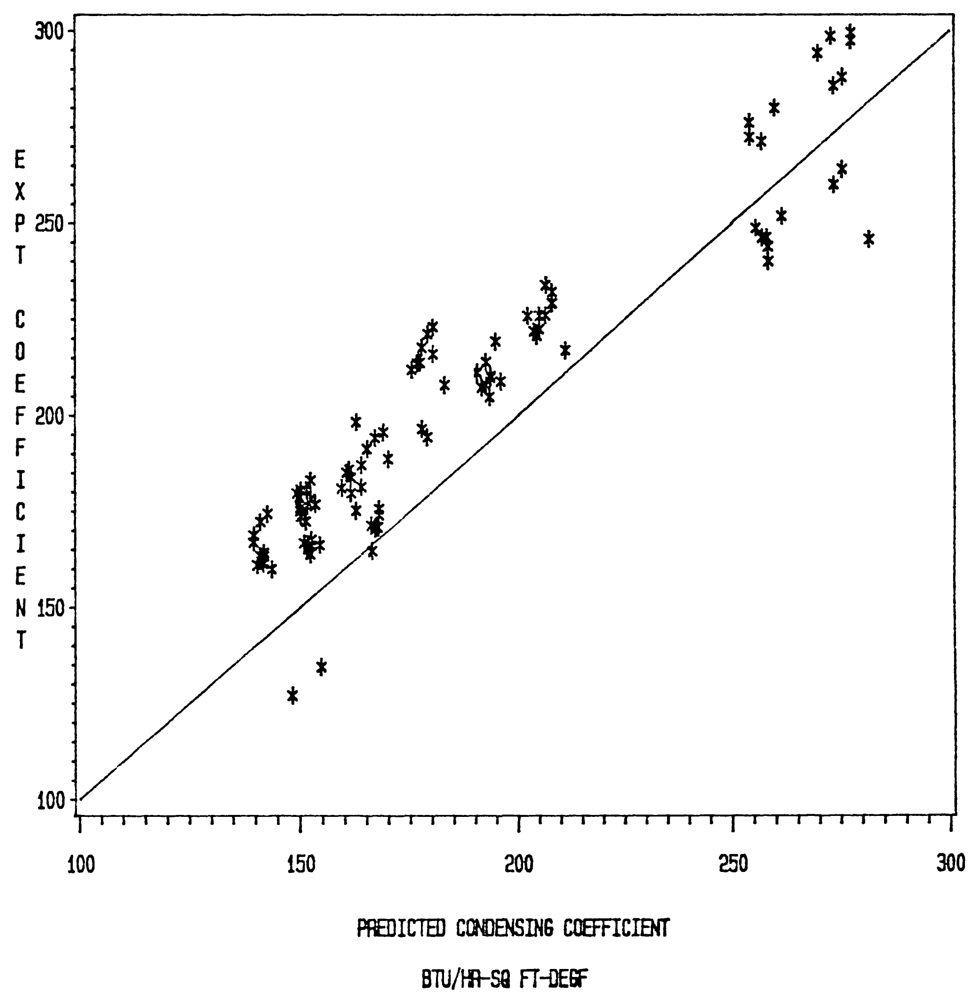

Figure 43. Toluene Comparison

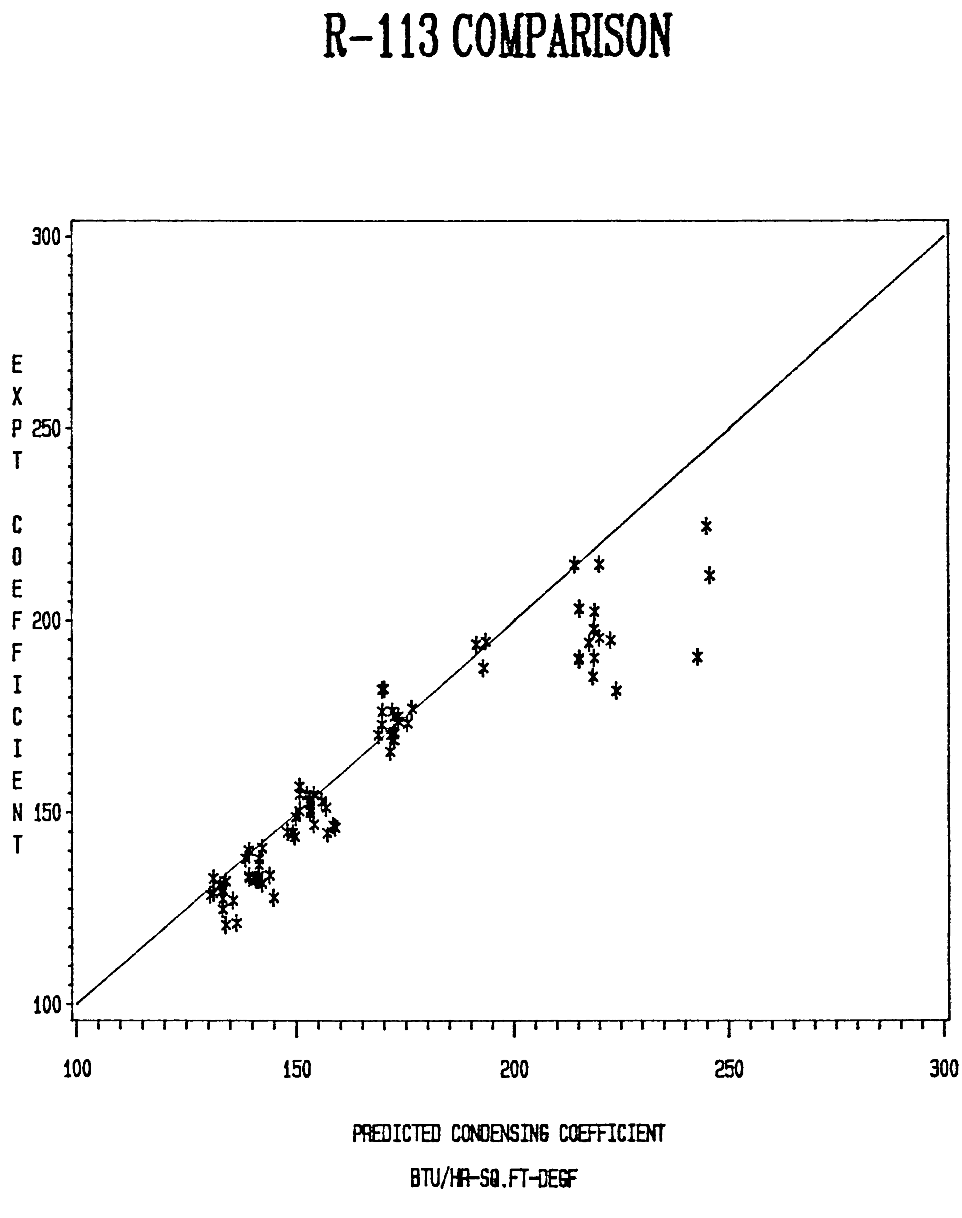

Figure 44. R-113 Comparison

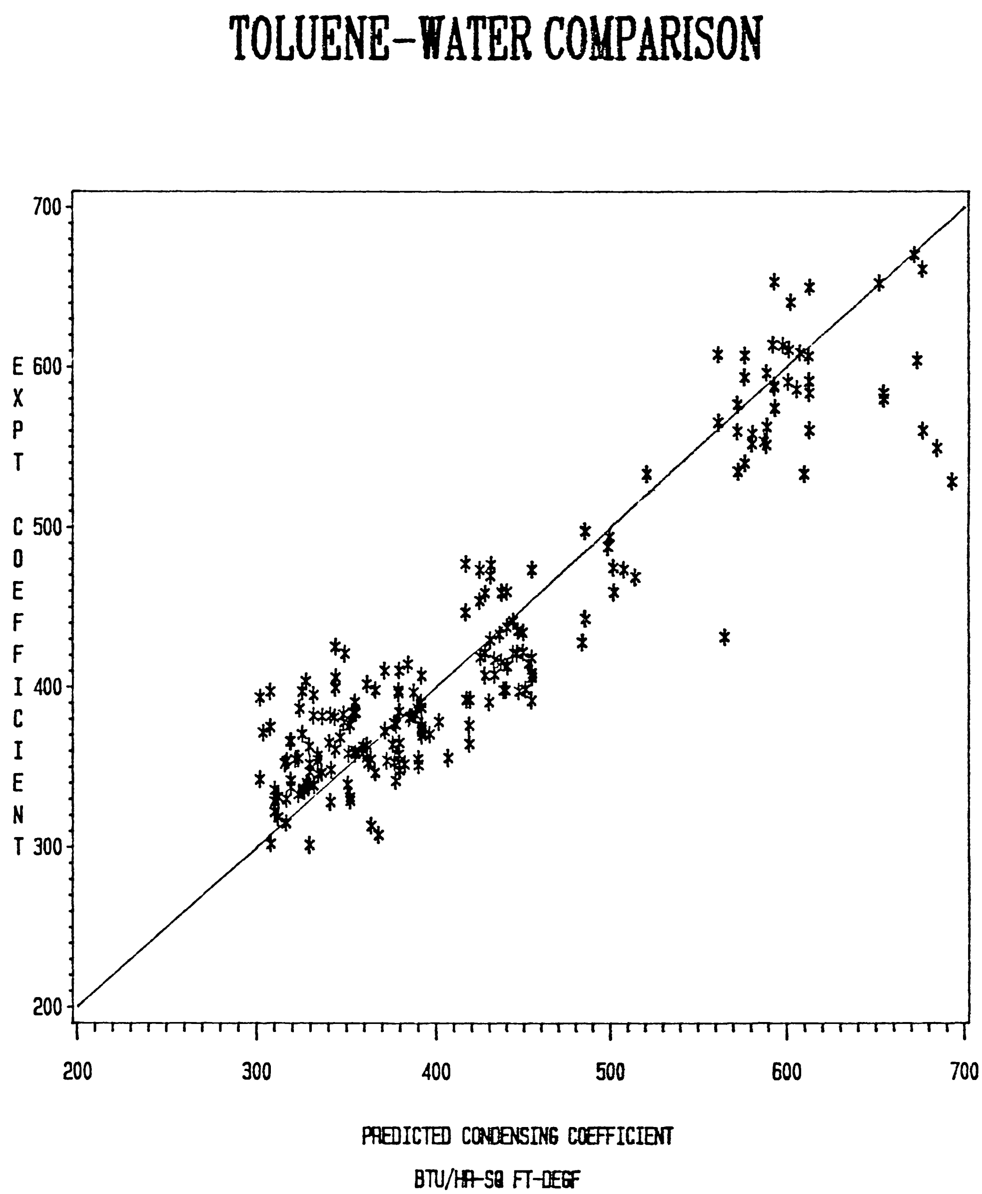

Figure 45. Toluene-Water Comparison

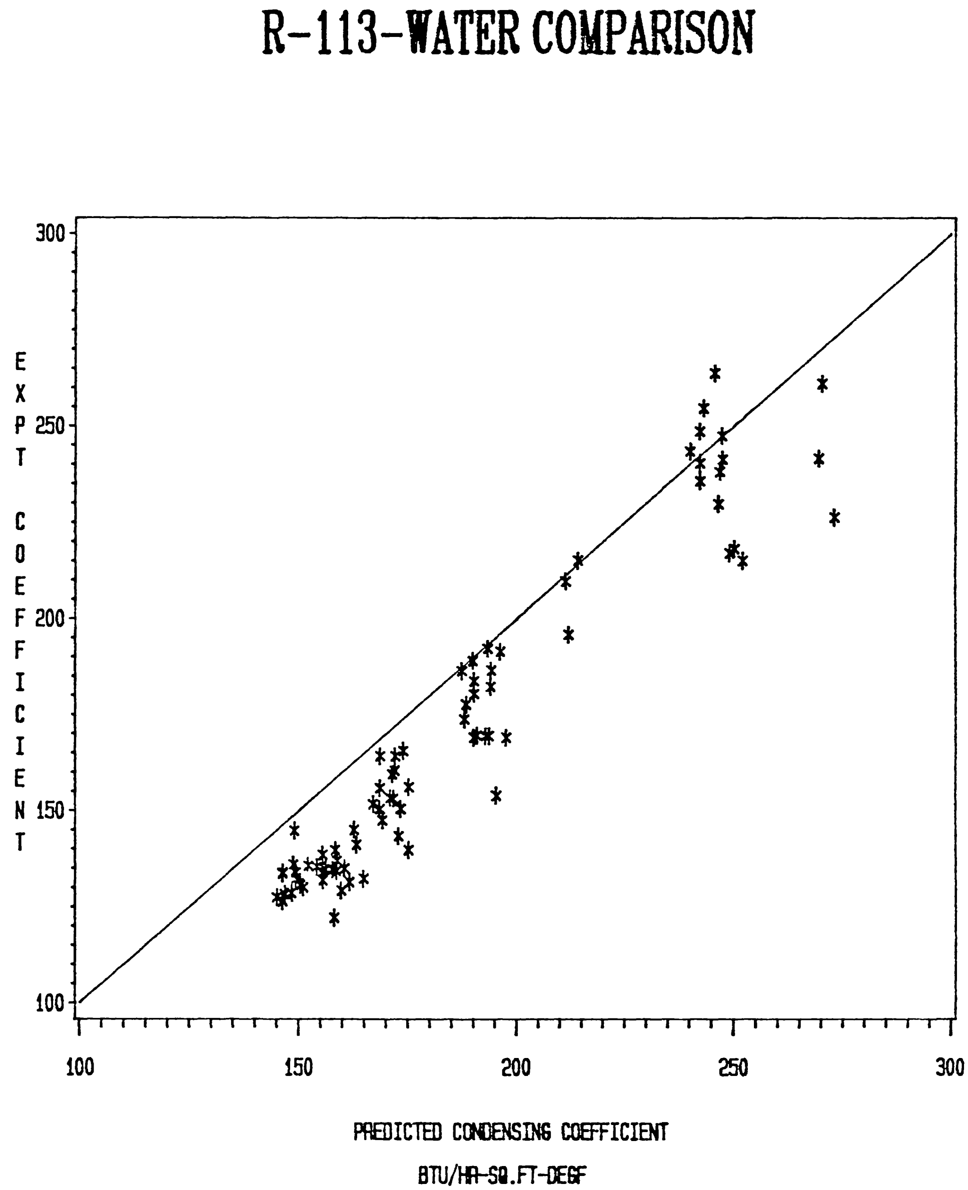

Figure 46. R-113-Water Comparison

lack of more extensive data on more mixtures, extrapolation is not recommended.

Summary

The data for condensation of immiscible liquids can be correlated using a pseudo-homogeneous liquid phase assumption. The correlations agree well with data on condensation of single components. The wave induced turbulence in the condensate increases the heat transfer rates due to the convective effects during single component as well as immiscible mixture condensation. These can be accounted for using condensate Prandtl number.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. Apparatus to study condensation was constructed and operated successfully. Data on condensation of three pure components and two immiscible mixtures were obtained. These data include the local heat fluxes, condensing coefficients, and condensate flow patterns.

2. Whenever an organic substance was present in the condensate, the condensate film flow was wavy.

3. The organic pure component data show condensing coefficients higher than the Nusselt theory predictions.

4. Three models were proposed to depict the condensate flow mechanisms for immiscible mixture condensation. The third model assuming a pseudo-homogeneous condensate was used to correlate the data for immiscible mixture condensation. The model appears to correlate the mixture data very well.

5. A rough flow regime boundary for immiscible mixture condensation can be established at condensate Reynolds number of 250. Below 250 the immiscible mixture condensate exhibits the film-drop and the film-drop-rivulet flow patterns with the film being organic. Above 250 the flow pattern changes to the shared surface mechanism.

6. All the pure component and mixture data can be correlated together by a simple method using pure component properties and the

condensate Prandtl number. The data show a trend of increased deviation from the Nusselt equation with increasing condensate Prandtl number.

Recommendations

1. Another condensing surface with higher thermal conductivity, such as brass, is needed to obtain higher heat fluxes. Data at very high heat fluxes and condensate Reynolds numbers may be obtained using a copper condensing surface.

2. The thermocouple locations in the condensation surface at each of the stations should be slightly staggered instead of being in a straight line in the direction of heat flow. This is to minimize the interference with the measured heat flux. Smaller thermocouples will also help.

3. The vapor inlet connection to the test cell is the bottleneck to obtaining high vapor flow rates. An oval opening similar to those seen in industrial air cooled heat exchangers, with cross section area roughly equal to that of the one inch vapor line, will facilitate high vapor flow rates without excessive pressure in the boiler.

4. Data on immiscible mixture condensation at condensate Reynolds numbers well above 250 are needed.

5. Data are needed to study the effects of high vapor velocity on the condensate flow mechanisms and condensing coefficients for immiscible mixtures.

6. The next set of experiments in this series should be performed using a brass and/or copper condensation surface, with condensate Reynolds numbers ranging from 200 to 10000.

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APPENDIX A

ANALYSIS OF FILMWISE CONDENSATION

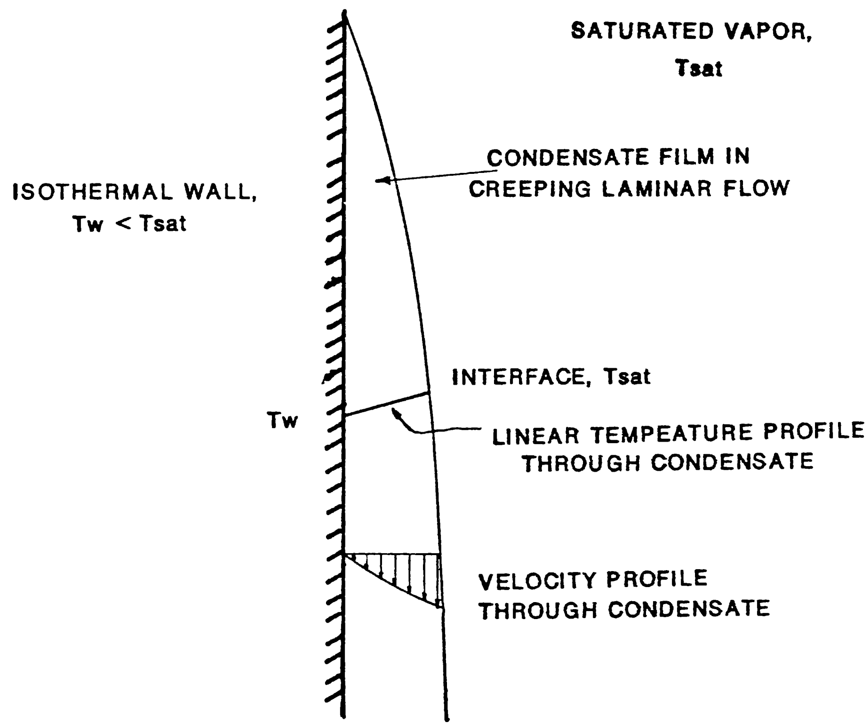

Figure 47. Filmwise Condensation

Assumptions Behind Nusselt Equation

1. Saturated vapor.
2. The liquid and the vapor are in thermodynamic equilibrium at the saturation temperature at the interface.
3. Heat is transferred by conduction only through the liquid film.
4. The temperature profile is linear through the liquid film.
5. The liquid and the solid surface are at the same temperature at their interface.
6. The solid surface is isothermal.
7. The liquid properties are not a function of temperature.

8. The vapor exerts neither shear nor normal stresses on the liquid surface.
9. The liquid has zero velocity at the liquid-solid interface (no-slip condition).
10. The sensible heat of subcooling the liquid is negligible compared to the latent heat load.

APPENDIX B

DISPLACEMENT CALCULATION

APPENDIX B

The Nelder and Mead (30) simplex was used in the following computer program to analyze the thermocouple displacements. The analysis was done using the IBM-3081D mainframe computer. An optimum displacement distance is found for each location so that the sum of the square of the errors is minimized. In this method, the three locations are treated as three axes (independent variables). In this three-dimensional space, a regular tetrahedron is constructed with one of the apexes at (0,0,0). However, the length of each side chosen is much smaller than that recommended by Nelder and Mead. The simplex method is a non-constrained technique and has a tendency to go wild if the starting size is large. It predicts all the thermocouples to be present at the condensing surface. Obviously, this is wrong and the maximum deviation possible is equal to the radius of the thermocouple well. This distance is 1/16 inch.

With proper starting size, the program predicted much smaller distances. For this optimization, the data used were from Runs 13 through 33. The predicted displacements were then used to analyze all the steam condensation data for Runs 13 through 53. The displacement results are given in Table II, page 51. Figure 7 illustrates the displacement at Station 2.

SOURCE CODE

```
$JOB
$PRINTOFF
C23456789
      DIMENSION T(25,20),NRUN(25),DLOC(5),NV(5),NF(5),NM(5),NB(5)
      COMMON /B/T,NST,J1,J2,J3,J4,MPT,DLOC
      DATA NV/1,17,18,19,20/
      DATA NF/16,5,7,14,13/
      DATA NM/2,4,8,10,11/
      DATA NB/3,6,9,12,15/
      DATA DLOC/3.,8.0,13.0,18.0,23.0/
      MPT=0
10    K=MPT+1
      READ(5,*,END= 99)NRUN(K)
      MPT=MPT+1
      READ(5,*) (T(MPT,I),I=2,10)
      READ(5,*) (T(MPT,I),I=11,20)
      T(MPT,1)=(T(MPT,17)+T(MPT,18)+T(MPT,19)+T(MPT,20))/4.0
      GO TO 10
99    DO 30 NST=1,5
      J1=NV(NST)
      J2=NF(NST)
      J3=NM(NST)
      J4=NB(NST)
      WRITE(6,20)NST
20    FORMAT(////,10X,' STATION NUMBER',I3,//)
      CALL OPT
30    CONTINUE
      WRITE(6,20)
      STOP
      END
      SUBROUTINE OPT
      DIMENSION X(10,10),F(10),XT(10),FDUM(10),DELF(10)
      DIMENSION XM(10),XR(10),XS(10)
      COMMON /A/XT,F,K,NDM
      DATA NDM/3/
      DATA ALP,BETA,GAMA/1.0,0.5,2.0/
      XS(1)=0.0
      XS(2)=0.0
      XS(3)=0.0
C
C
      ILIM=NDM+1
      AILIM=ILIM
      ANDM=NDM
      D1=(SQRT(ANDM+1.)+ANDM-1.)/ANDM/SQRT(2.0)
      D2=(SQRT(ANDM+1.)-1.)/ANDM/SQRT(2.0)
CCCCCCCCCCCCCCCCC
      D1=D1/80.0
      D2=D2/40.0
CCCCCCCCCCCCCCCCC
      DO 10 I=1,NDM
10    X(1,I)=0.0
      DO 20 I=2,ILIM
      DO 20 J=1,NDM
      JCOMP=I-1
      IF(J.EQ.JCOMP) GO TO 40
      X(I,J)=D2
      GO TO 20
40    X(I,J)=D1
20    CONTINUE
      DO 5 I=1,ILIM
      DO 5 J=1,NDM
5     X(I,J)=X(I,J)+XS(J)
      DO 100 I=1,ILIM
100   F(I)=0.0
      DO 50 K=1,ILIM
      DO 60 M=1,NDM
 60   XT(M)=X(K,M)
      CALL FUN
50    CONTINUE
      ICNT=0
6000  FH=F(1)
```

```
      NDUM1=1
      DO 110 K=2,ILIM
      IF(FH.LT.F(K)) GO TO 120
      GO TO 110
120   FH=F(K)
      NDUM1=K
110   CONTINUE
      I=0
      DO 140 K=1,ILIM
      IF(NDUM1.EQ.K) GO TO 140
      I=I+1
      FDUM(I)=F(K)
140   CONTINUE
      DO 150 I=1,NDM
150   DELF(I)=FH-FDUM(I)
      DELFS=DELF(1)
      DO 180 L=1,NDM
180   IF(DELFS.GT.DELF(L))DELFS=DELF(L)
      FS=FH-DELFS
      FL=F(1)
      NDUM2=1
      DO 160 K=2,ILIM
      IF(FL.GT.F(K)) GO TO 170
      GO TO 160
170   FL=F(K)
      NDUM2=K
160   CONTINUE
CCCCCC
CCCCCCCC
       PRINT 161,((X(L1,L2),L2=1,NDM),F(L1),L1=1,ILIM)
161    FORMAT(2X,4(3(F7.4,1X),F6.1,2X))
CCCCCC
CCCCCCCC
      ANDM=NDM
      DO 200 K=1,NDM
      SUM=0.0
      DO 210 I=1,ILIM
      IF(I.EQ.NDUM1) GO TO 210
      SUM=SUM+X(I,K)
210   CONTINUE
200   XM(K)=SUM/ANDM
      DO 220 K=1,NDM
220   XR(K)=XM(K)+ALP*(XM(K)-X(NDUM1,K))
      DO 230 J=1,NDM
230   XT(J)=XR(J)
      K=NDM+3
      CALL FUN
      FR=F(K)
      IF(F(NDM+3).GE.FL) GO TO 1000
      DO 300 N=1,NDM
300   XT(N)=XM(N)+GAMA*(XR(N)-XM(N))
      K=NDM+4
      CALL FUN
      IF(F(K).GE.FL) GO TO 320
      DO 340 J=1,NDM
340   X(NDUM1,J)=XT(J)
      F(NDUM1)=F(NDM+4)
      GO TO 5000
320   DO 350 J=1,NDM
350   X(NDUM1,J)=XR(J)
      F(NDUM1)=F(NDM+3)
      GO TO 5000
1000  IF(FS.GT.FR) GO TO 320
      IF(FR.GE.FH) GO TO 1600
      DO 1510 J=1,NDM
1510  X(NDUM1,J)=XR(J)
1600  DO 1520 J=1,NDM
1520  XT(J)=XM(J)+BETA*(X(NDUM1,J)-XM(J))
      K=NDM+5
      CALL FUN
      IF(F(K).LT.FH) GO TO 1700
      DO 1720 I=1,ILIM
```

```
      DO 1720 J=1,NDM
1720  X(I,J)=(X(I,J)+X(NDUM2,J))*0.5
      DO 1770 K=1,ILIM
      DO 1780 J=1,NDM
1780  XT(J)=X(K,J)
      CALL FUN
1770  CONTINUE
      GO TO 5000
1700  DO 1750 J=1,NDM
1750  X(NDUM1,J)=XT(J)
      F(NDUM1)=F(NDM+5)
5000  ICNT=ICNT+1
      IF(ICNT.LT.1000)GO TO 9999
      PRINT,' TOO MANY ITERATIONS'
      RETURN
9999  FSUM=0.0
      DO 5010 M=1,ILIM
5010  FSUM=FSUM+F(M)
      FMEAN=FSUM/AILIM
      FDIF=0.0
      DO 5020 M=1,ILIM
5020  FDIF=FDIF+(F(M)-FMEAN)**2
      VAR=FDIF/ANDM
      STDAV=SQRT(VAR)
      SDLIM=0.01*FMEAN
      ABFMN=ABS(FMEAN)
      IF(ABFMN.LT.1.0)GO TO 5100
      IF(STDAV.GT.SDLIM) GO TO 6000
      GO TO 7000
5100  IF(STDAV.GT.0.01)GO TO 6000
7000  DO 8000 J=1,NDM
      S=0.0
      DO 8100 I=1,ILIM
8100  S=S+X(I,J)
8000  XT(J)=S/AILIM
      SUMSQ=0.0
      DO 5400 J=1,NDM
5400  SUMSQ=SUMSQ+XT(J)**2
      IF(SUMSQ.GT.1.0) GO TO 5450
      D4=1.0
      DO 5465 I=1,ILIM
      SMHSQ=0.0
      DO 5460 J=1,NDM
5460  SMHSQ=SMHSQ+(X(I,J)-XT(J))**2
      SDNSM=SMHSQ/NDM
      IF(SDNSM.GT.0.04) D4=-1.0
5465  CONTINUE
      IF(D4.EQ.-1.0) GO TO 6000
      GO TO 5470
5450  D3=1.0
      DO 5500 J=1,NDM
      SDL=XT(J)*0.5
      XDIF=0.0
      DO 5600 I=1,ILIM
5600  XDIF=XDIF+(X(I,J)-XT(J))**2
      STDL=SQRT(XDIF/ANDM)
      IF(STDL.GT.SDL) D3=-1.0
5500  CONTINUE
      IF(D3.EQ.-1.0) GO TO 6000
5470  K=NDM+2
      CALL FUN
      IF(F(NDM+2).GT.FL) GO TO 8200
      PRINT 1921
1921  FORMAT(1H1,/)
      PRINT 2541, (XT(J),J=1,NDM)
2541  FORMAT(//,' THE MINIMUM IS AT',/,5X,10F10.5)
      PRINT 2571,F(NDM+2)
2571  FORMAT(///,' THE MINIMUM VALUE IS',5X,E15.5)
      GO TO 9000
8200  PRINT 1921
      PRINT 2541,(X(NDUM2,J),J=1,NDM)
      PRINT 2571,FL
```

```
9000  PRINT 9100,ICNT
9100  FORMAT(//,' NO OF CONVERGENCE CHECKS = ',I5)
      PRINT 1921
      RETURN
      END
      SUBROUTINE FUN
      COMMON /A/XT,F,K,NDM
      COMMON /B/T,NST,J1,J2,J3,J4,MPT,DLOC
      DIMENSION C(3),D(3),T(25,20),DLOC(5)
      DIMENSION XT(10),F(10)
      C(1)=0.25
      C(2)=0.5
      C(3)=0.75
      ER=0.0
      DO 10 I=1,MPT
      SYXW=0.0
      SY=0.0
      SI=NDM
      SXW=0.0
      SXWXW=0.0
      D(1)=T(I,J2)
      D(2)=T(I,J3)
      D(3)=T(I,J4)
      DO 20 J=1,NDM
      SYXW=SYXW+D(J)*(C(J)-XT(J))
      SY=SY+D(J)
      SXW=SXW+C(J)-XT(J)
20    SXWXW=SXWXW+(C(J)-XT(J))**2
      A1=(SYXW*SI-SY*SXW)/(SI*SXWXW-SXW*SXW)
      A0=(SY-A1*SXW)/SI
      DO 30 J=1,NDM
      ER=ER+ABS( A0+A1*(C(J)-XT(J) - D(J) )
30    CONTIUE
10    CONTINUE
      F(K)=ER/MPT
C                 PRINT,F(K)
      RETURN
      END
$ENTRY
13
163.2,139.6,158.1,183.0,133.0,179.7,152.9,124.0,149.7
138.6,120.6,174.4,175.9,110.1,185.9,210.8,210.8,210.8,210.8
14
162.2,138.3,157.6,182.4,132.4,178.9,152.3,123.2,149.1
138.0,119.8,173.7,175.1,109.7,184.6,210.1,210.0,210.0,210.0
15
161.9,138.3,157.4,182.5,132.6,179.3,152.4,121.2,149.8
137.9,119.7,173.8,175.3,109.3,184.1,210.1,210.1,210.1,210.1
16
162.4,138.0,156.1,180.5,131.3,177.4,151.1,119.9,149.0
136.7,118.9,172.6,174.0,108.3,183.8,209.9,210.0,210.1,210.1
17
162.0,138.1,156.0,180.4,130.7,177.2,150.8,120.6,148.8
136.4,118.5,172.1,173.5,108.1,183.4,209.5,209.5,209.7,209.8
18
161.7,138.2,155.9,180.1,131.3,177.0,150.6,120.1,148.7
136.2,118.4,172.0,173.4,107.7,183.2,209.4,209.4,209.5,209.7
19
162.9,139.4,157.9,182.7,133.1,178.6,152.5,122.1,150.7
137.8,120.7,170.4,175.5,109.4,184.9,210.2,210.2,210.2,210.2
20
162.7,139.2,157.6,182.4,133.1,178.4,151.8,121.0,150.2
138.1,120.0,173.3,175.0,109.2,184.4,209.8,209.7,209.9,209.9
21
162.3,139.2,157.1,181.5,132.4,178.5,151.9,121.1,150.4
137.8,120.0,173.6,175.5,109.3,184.9,210.5,210.5,210.5,210.5
22
162.3,138.7,156.8,181.4,132.2,178.3,151.6,120.8,150.0
137.6,119.6,173.3,175.0,108.6,184.6,210.2,210.1,210.2,210.2
23
162.5,138.9,157.2,181.6,132.4,178.5,151.8,121.5,150.0
137.7,119.3,173.2,174.9,108.4,184.3,209.9,209.9,210.0,210.1
```

```
24
163.3,140.6,158.0,181.5,134.3,178.9,153.1,123.4,151.6
140.2,122.3,174.6,175.8,112.3,185.3,210.1,210.0,210.0,210.0
25
163.3,140.1,157.7,181.3,133.6,178.0,152.5,123.0,151.0
139.7,121.9,174.1,175.3,111.7,184.5,209.7,209.7,209.8,209.8
26
163.4,140.4,157.8,181.4,133.9,178.2,152.6,123.0,151.1
139.8,122.0,173.9,175.1,111.8,184.5,209.6,209.5,209.6,209.7
27
163.4,140.1,157.8,181.4,133.7,178.1,152.7,122.9,151.3
139.9,122.0,174.1,175.2,112.0,184.7,209.8,210.0,210.2,210.2
28
164.8,142.4,159.5,182.6,136.3,179.6,154.9,126.1,153.3
142.0,124.6,175.5,177.2,114.8,186.5,211.0,211.0,211.0,211.0
29
165.2,142.6,159.7,182.8,136.4,179.8,154.8,125.9,153.6
142.0,124.8,175.5,177.1,114.5,186.4,210.8,210.7,210.8,210.7
30
165.2,142.8,159.8,182.7,136.7,179.8,155.0,126.1,153.3
142.0,124.6,175.4,176.9,114.5,186.0,210.4,210.4,210.4,210.4
31
165.1,142.7,159.9,183.0,136.8,179.9,155.0,126.1,154.2
142.7,125.5,176.3,177.6,115.1,186.6,211.0,211.0,211.0,211.0
32
164.9,142.3,159.7,182.8,136.4,179.9,155.0,126.0,154.1
143.0,125.4,176.3,177.5,115.3,186.1,210.7,210.7,210.7,210.7
33
164.7,142.0,159.5,182.6,136.5,179.7,154.9,126.0,154.1
142.6,125.2,176.0,177.3,115.0,185.8,210.5,210.4,210.5,210.5
$IBSYS
```

APPENDIX C

STEAM CONDENSATION

SAMPLE CALCULATIONS

Sample Run #35

Steam Properties

	Vapor		Liquid
k Btu/hr•ft•°F			0.393
ρ lb/ft^3	0.03255		60.0
λ Btu/lb		974.8	
μ lb/hr•ft			0.7163
Cp Btu/lb•°F			1.0

SS 304 thermal conductivity = 9.0 Btu/hr•ft•°F

Station #1

Location	Displacement (inch)	Temperature (°F)
Vapor	-	209.1
Front	0.0160	185.2
Middle	0.0151	164.7
Back	0.0123	143.0

Best fit straight line for the temperature gradient through the SS 304 plate:

$y = A_0 + A_1 x$

$y \equiv$ temperature, °F

$x \equiv$ distance from front surface, inch

x	y
0.25 - 0.0160	185.2
0.5 - 0.0151	164.7
0.75 - 0.0123	143.0

$\Sigma\, xy = 228.69$ $\qquad \Sigma\, y = 492.9$

$\Sigma\, x = 1.4566$ $\qquad \Sigma\, x^2 = 0.8341$

$\Sigma i = 3$

$$A_1 = \frac{\Sigma\, xy * \Sigma\, i - \Sigma\, y * \Sigma\, x}{\Sigma\, i * \Sigma\, x^2 - \Sigma\, x * \Sigma\, x} = -83.78$$

$$A_0 = \frac{\Sigma\, y - A_1\, \Sigma\, x}{\Sigma\, i} = 204.98$$

At the front surface, x = 0

$T_s = 204.98 - 83.78 * x$

$= 204.98°F$

ΔT across the condensate

$= T_v - T_s$

$= 209.1 - 204.98$

$= 4.12°F$

Heat flux through the SS 304 plate

$$\frac{Q}{A} = K\,\frac{\Delta T}{\Delta x}$$

$$= \frac{9.0 * [204.98 - (204.98 - 83.78 * 1)]}{1/12}$$

$$= 9048\ \text{Btu/hr}\cdot\text{ft}^2$$

Condensing heat transfer coefficient

$$h = \frac{Q/A}{\Delta T} = \frac{9048}{4.12}$$

$$= 2196\ \text{Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

Prediction based on Nusselt's equation

$$h = [\frac{k_l^3 \ \rho_l \ (\rho_l - \rho_v) \ g \ \lambda}{4 \ \mu_l \ (T_v - T_s) \ x}]^{1/4} * [1 + 0.68 \ \frac{Cp_l \ (T_v - T_s)}{\lambda}]^{1/4}$$

$$= [\frac{0.393^3 * 60 * (60 - 0.03255) * 32 * 3600^2 * 974.8}{4 * 0.7163 * 4.1 * 3/12}]^{1/4}$$

$$* [1 + 0.68 * \frac{1 * 4.1}{974.8}]^{1/4}$$

$$= 2343 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

$$\% \text{ Error} = \frac{2196 - 2343}{2343} * 100$$

$$= -6.3\%$$

Condensate Reynolds number and condensation number

Condensate rate = 41.6 ml/min

$$= 41.6 * \frac{1}{1000} * \frac{1}{28.32} * 60 * 60.0$$

$$\frac{ml}{min} * \frac{lit}{ml} * \frac{ft^3}{lit} * \frac{min}{hr} * \frac{lb}{ft^3}$$

$$= 5.29 \text{ lb/hr}$$

Condensate loading

$$\Gamma = \frac{\text{condensate rate}}{\text{perimeter}}$$

$$= \frac{5.29}{2/12} = 31.73 \text{ lb/hr-ft}$$

Local condensate Reynolds number

$$= \frac{4\Gamma}{\mu_l}$$

$$= \frac{4 * 31.73 * 3/26}{0.7163}$$

$$= 20.45$$

Local condensation number

$$= h \left[\frac{k_l^3 \rho_l (\rho_l - \rho_v) g}{\mu_l^2}\right]^{-1/3}$$

$$= 0.3915$$

SOURCE CODE

```
$JOB
C23456789
      DIMENSION T(70,20),NRUN(70),DLOC(5),NV(5),NF(5),NM(5),NB(5)
      DIMENSION XT(3,5),C(3),D(3)
      DIMENSION XP(70),YP(70),WPR(70),WSE(70)
      DATA NV/1,17,18,19,20/
      DATA NF/16,5,7,14,13/
      DATA NM/2,4,8,10,11/
      DATA NB/3,6,9,12,15/
      DATA DLOC/3.,8.0,13.0,18.0,23.0/
      DATA XT/0.016,0.0151,0.0123,0.0144,0.0144,-0.0013,0.024,0.0335,-0.
     #0113,0.0144,0.0229,0.0019,0.0323,0.0256,0.0008/
C     DATA XT/15*0.0/
      DATA LF/11/
      MPT=0
10    K=MPT+1
      READ(5,*,END= 99)NRUN(K)
      MPT=MPT+1
      READ(5,*) (T(MPT,I),I=2,10)
      READ(5,*) (T(MPT,I),I=11,20)
      READ(5,*)WPR(MPT),WSE(MPT)
      T(MPT,1)=(T(MPT,17)+T(MPT,18)+T(MPT,19)+T(MPT,20))/4.0
      GO TO 10
99    HN=4385.75
      C(1)=0.25
      C(2)=0.5
      C(3)=0.75
      DO 60 NST=1,5
      J1=NV(NST)
      J2=NF(NST)
      J3=NM(NST)
      J4=NB(NST)
      WRITE(6,21)
21    FORMAT(1H1,//////,' ')
      WRITE(6,20)NST,(XT(J,NST),J=1,3)
20    FORMAT(18X,' STATION NUMBER',I3,/,13X,3F10.5,//,8X,'RUN',1X,
     #' TV   ','   TF   ','   TM   ','   TB   ',2X,'DT',5X,
     #'H',5X,'HNU',5X,'% ERR',4X,'Q/A',7X,'X',7X,'Y',5X,'ML/M',/)
      DO 40 I=1,MPT
      SYXW=0.0
      SY=0.0
      SI=3
      SXW=0.0
      SXWXW=0.0
      D(1)=T(I,J2)
      D(2)=T(I,J3)
      D(3)=T(I,J4)
      DO 30 J=1,3
      SYXW=SYXW+D(J)*(C(J)-XT(J,NST))
      SY=SY+D(J)
      SXW=SXW+C(J)-XT(J,NST)
30    SXWXW=SXWXW+(C(J)-XT(J,NST))**2
      A1=(SYXW*SI-SY*SXW)/(SI*SXWXW-SXW*SXW)
      A0=(SY-A1*SXW)/SI
      DT=T(I,J1)-A0
      Q=-A1*108.0
      H=-A1*108.0/DT
      HNU=HN/(DLOC(NST)*DT)**0.25
      HNU=HNU*(1.0+0.68*DT/974.8)**0.25
      PCER=(H-HNU)/HNU*100.0
      XP(I)=WPR(I)*DLOC(NST)*0.1638
      YP(I)=H/5610.7
      WRITE(LF,210)XP(I),YP(I)
210   FORMAT(1X,F10.5,2X,F8.4)
40    WRITE(6,50)NRUN(I),T(I,J1),T(I,J2),T(I,J3),T(I,J4),DT,H,HNU,PCER,Q
     #,XP(I),YP(I),WPR(I)
50    FORMAT(8X,I2,4(1X,F5.1),1X,F5.1,2(1X,F6.0),2X,F7.1,2X,F7.0,2X,F6.2
     #,2X,F6.4,2X,F6.2)
      WRITE(LF,220)
220   FORMAT(1X,'   ')
60    CONTINUE
      WRITE(6,21)
```

```
      STOP
      END
$ENTRY
13
163.2,139.6,158.1,183.0,133.0,179.7,152.9,124.0,149.7
138.6,120.6,174.4,175.9,110.1,185.9,210.8,210.8,210.8,210.8
44.7,84.0
14
162.2,138.3,157.6,182.4,132.4,178.9,152.3,123.2,149.1
138.0,119.8,173.7,175.1,109.7,184.6,210.1,210.0,210.0,210.0
44.7,83.1
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161.9,138.3,157.4,182.5,132.6,179.3,152.4,121.2,149.8
137.9,119.7,173.8,175.3,109.3,184.1,210.1,210.1,210.1,210.1
45.0,88.1
16
162.4,138.0,156.1,180.5,131.3,177.4,151.1,119.9,149.0
136.7,118.9,172.6,174.0,108.3,183.8,209.9,210.0,210.1,210.1
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162.0,138.1,156.0,180.4,130.7,177.2,150.8,120.6,148.8
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44.7,82.9
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161.7,138.2,155.9,180.1,131.3,177.0,150.6,120.1,148.7
136.2,118.4,172.0,173.4,107.7,183.2,209.4,209.4,209.5,209.7
34.5,87.1
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138.1,120.0,173.3,175.0,109.2,184.4,209.8,209.7,209.9,209.9
47.3,83.8
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162.3,139.2,157.1,181.5,132.4,178.5,151.9,121.1,150.4
137.8,120.0,173.6,175.5,109.3,184.9,210.5,210.5,210.5,210.5
45.0,97.5
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137.6,119.6,173.3,175.0,108.6,184.6,210.2,210.1,210.2,210.2
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162.5,138.9,157.2,181.6,132.4,178.5,151.8,121.5,150.0
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163.3,140.6,158.0,181.5,134.3,178.9,153.1,123.4,151.6
140.2,122.3,174.6,175.8,112.3,185.3,210.1,210.0,210.0,210.0
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142.0,124.6,175.5,177.2,114.8,186.5,211.0,211.0,211.0,211.0
43.5,105.0
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165.2,142.6,159.7,182.8,136.4,179.8,154.8,125.9,153.6
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164.9,142.3,159.7,182.8,136.4,179.9,155.0,126.0,154.1
143.0,125.4,176.3,177.5,115.3,186.1,210.7,210.7,210.7,210.7
42.0,108.0
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145.7,130.9,176.4,178.0,120.7,187.5,209.1,209.0,209.0,209.0
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38.4,68.8
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162.2,149.4,186.0,186.5,143.0,192.9,210.3,210.2,210.3,210.2
32.0,76.0
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177.2,161.3,173.9,190.2,158.1,188.2,171.0,150.7,169.5
162.2,149.5,185.7,186.1,142.8,192.4,209.6,209.6,209.6,209.6
31.6,78.0
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176.9,160.7,173.4,190.0,157.3,187.9,170.3,149.9,169.0
161.5,148.7,185.1,185.6,141.9,191.9,209.4,209.4,209.4,209.3
31.6,76.0
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174.6,157.2,171.5,189.8,153.7,186.8,167.8,145.7,166.3
158.3,144.7,184.0,184.7,137.1,191.2,210.0,209.9,209.9,209.9
34.4,82.0
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174.6,157.6,171.6,189.8,154.0,186.7,167.8,145.9,166.1
158.1,144.1,183.7,184.2,136.9,190.9,209.5,209.4,209.5,209.5
34.4,82.0
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174.4,157.2,171.4,189.6,153.7,186.5,167.5,145.4,165.8
157.7,143.7,183.3,183.9,136.4,190.5,209.3,209.2,209.2,209.2
34.0,82.0
$IBSYS
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RESULTS

Nomenclature for Data Printout

TV	vapor temperature, °F
TF	front thermocouple, °F
TM	middle thermocouople, °F
TB	back thermocouple, °F
DT	ΔT_f, °F
H	condensing coefficient, Btu/hr•ft^2•°F
HNU	H calculated by Nusselt equation
%ERR	(H - HNU)/HNU * 100
Q/A	local heat flux, Btu/hr•ft^2
X	local condensate Reynolds number
Y	local condensation number
ML/M	condensate volumetric flow rate, ml/min

STATION NUMBER 1

0.01600 0.01510 0.01230

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
13	210.8	185.9	163.2	139.6	3.3	3036.	2480.	22.4	9927.	21.97	0.5411	44.70
14	210.0	184 6	162 2	138.3	3.7	2687.	2405.	11.7	9927.	21.97	0.4789	44.70
15	210.1	184.1	161 9	138 3	4.5	2174	2288.	-5.0	9820.	22.11	0 3874	45.00
16	210 0	183 8	162 4	138 0	4 5	2195	2293	-4 3	9821	21 87	0 3912	44 50
17	209 6	183 4	162 0	138 1	4 8	2028	2254	-10 1	9713	21 97	0 3614	44 70
18	209 5	183 2	161 7	138 2	5 1	1896	2221	-14 6	9649	16 95	0 3380	34 50
19	210 2	184.9	162.9	139.4	3 9	2476.	2367.	4.6	9756.	23.10	0 4412	47.00
20	209 8	184.4	162 7	139.2	4 2	2333.	2336.	-0.1	9692.	23 24	0.4158	47.30
21	210 5	184.9	162.3	139.2	4 3	2271	2314.	-1.9	9799	22.11	0 4047	45.00
22	210 2	184 6	162 3	138 7	4 1	2422	2349	3 1	9842	21.87	0 4317	44 50
23	210 0	184 3	162 5	138 9	4 3	2258	2314	-2 4	9735	21 62	0 4024	44 00
24	210 0	185 3	163 3	140 6	3 9	2476	2377	4 1	9584	21 62	0 4413	44 00
25	209 7	184.5	163 3	140 1	4 3	2205.	2314	-4.7	9520	20.84	0.3930	42 40
26	209 6	184 5	163 4	140 4	4 3	2188	2313.	-5 4	9456.	20.64	0.3899	42 00
27	210.0	184.7	163 4	140 1	4 3	2211.	2313.	-4 4	9563	20 84	0 3941	42.40
28	211 0	186 5	164 8	142 4	3 9	2409	2369	1 7	9456	21 38	0 4294	43 50
29	210 7	186 4	165 2	142 6	3 8	2474	2389	3 6	9391	21 62	0 4409	44 00
30	210 4	186 0	165 2	142 8	4 1	2264	2345	-3 4	9263	21 03	0 4036	42 80
31	211.0	186.6	165.1	142.7	3 9	2424.	2375.	2.0	9413.	20.84	0.4320	42.40
32	210.7	186.1	164.9	142.3	4.0	2321.	2351.	-1.3	9391.	20.64	0.4137	42.00
33	210 5	185 8	164 7	142 0	4.1	2298	2345.	-2.0	9392.	20.84	0 4096	42.40
34	209 5	185.5	164 6	142 9	4 1	2226.	2343.	-5.0	9134.	20.15	0.3968	41.00
35	209.1	185 2	164 7	143 0	4 1	2195.	2341	-6 2	9048	20.44	0 3913	41 60
36	209.0	185 0	164 8	143 5	4.6	1939	2279.	-14 9	8898	20.44	0.3456	41 60
37	208.7	184.7	164 3	142.7	4.3	2100.	2317.	-9 4	9005.	20.44	0.3742	41.60
38	208.7	184 9	164.3	142.8	4.2	2165.	2334.	-7.2	9027.	20.05	0.3859	40.80
39	209.0	187.5	168.5	148 9	3.5	2353.	2435.	-3 4	8276	18.82	0.4194	38.30
40	208 7	187.2	168 7	149 3	3 8	2143.	2390	-10.3	8126	19.31	0 3819	39.30
41	208 6	187 1	168 8	149 4	3 8	2127	2388	-11.0	8083	19 02	0.3790	38 70
42	208 3	186 9	168 8	149 7	3 9	2019	2365.	-14 6	7976	18 82	0.3599	38 30
43	209.7	188.3	169.2	150.0	3.6	2287.	2422.	-5.6	8212.	19.66	0.4076	40.00
44	209 2	187 9	169 5	150 4	3.8	2110	2387.	-11.6	8040.	18.87	0.3760	38.40
45	209 8	187.8	168 1	148 3	3.7	2314	2411.	-4 0	8469.	18.87	0 4125	38.40
46	209 5	187 7	168 7	149 0	3 7	2225	2400	-7 3	8298	18 87	0 3966	38 40
47	210 2	192.9	177 0	160 7	2 3	2944.	2694	9 3	6904	15.72	0 5248	32 00
48	209 6	192 4	177 2	161 3	2 7	2511.	2612	-3 9	6668.	15 53	0 4475	31 60
49	209.4	191.9	176.9	160.7	2.8	2389.	2577.	-7.3	6690.	15.53	0.4259	31.60
50	209.9	191.2	174.6	157.2	2 8	2587	2573.	0 5	7290.	16.90	0.4611	34.40
51	209.5	190.9	174.6	157 6	3.0	2372.	2531.	-6.3	7140.	16 90	0.4228	34.40
52	209 2	190 5	174 4	157 2	3 1	2309	2514.	-8.2	7140	16.71	0 4115	34 00

STATION NUMBER 2

0.01440 0.01440 -0.00130

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
13	210.8	183.0	158 1	133.0	5 2	2017.	1729.	16.6	10468	58.57	0 3594	44.70
14	210 1	182 4	157 6	132.4	5.1	2071	1741.	19 0	10469.	58.57	0 3691	44.70
15	210 1	182.5	157.4	132 6	5 1	2039.	1735.	17.5	10446.	58.97	0.3633	45.00
16	209 9	180 5	156 1	131 3	7 1	1447	1599	-9 5	10301	58 31	0 2580	44 50
17	209 5	180 4	156 0	130.7	6 5	1600	1635	-2 1	10407	58 57	0 2852	44 70
18	209 4	180 1	155 9	131 3	7 2	1420	1594	-10 9	10218	45 21	0 2530	34 50
19	210.2	182 7	157.9	133.1	5.1	2033.	1736.	17.1	10384.	61.59	0.3624	47.00
20	209 8	182 4	157 6	133.1	5 2	1987	1729.	14 9	10321.	61 98	0.3541	47.30
21	210 5	181 5	157 1	132.4	6 8	1516.	1618.	-6.3	10280.	58.97	0 2702	45.00
22	210 2	181 4	156 8	132 2	6 6	1564	1630	-4 0	10300	58 31	0 2787	44 50
23	209 9	181 6	157 2	132 4	6 0	1712	1667	2 7	10301	57 66	0 3051	44 00
24	210 1	181 5	158 0	134 3	7 3	1362	1591	-14 4	9882	57 66	0 2428	44 00
25	209.7	181.3	157 7	133.6	6 8	1474	1618	-8 9	9987	55.56	0.2627	42 40
26	209.6	181.4	157 8	133 9	6.7	1484	1623	-8 5	9945.	55 04	0.2645	42 00
27	209.8	181.4	157 8	133 7	6 8	1474	1618.	-6 9	9988	55 56	0.2627	42 40
28	211 0	182 6	159 5	136 3	7 5	1296	1579	-17 9	9693	57 00	0 2310	43 50
29	210 8	182 8	159 7	136 4	7 0	1385	1604	-13 7	9715	57 66	0 2468	44 00
30	210 4	182.7	159 8	136 7	6 9	1397	1611	-13 3	9631	56 09	0 2489	42 80
31	211.0	183.0	159.9	136.8	7.1	1354	1597.	-15.2	9672	55.56	0.2414	42.40
32	210.7	182.8	159.7	136.4	6 9	1405	1610	-12.8	9715.	55.04	0.2504	42.00
33	210.5	182 6	159.5	136 5	7.1	1358.	1599.	-15.1	9651.	55.56	0.2421	42.40
34	209 5	182 5	160 2	137 7	6 7	1392	1620	-14 1	9380	53 73	0 2481	41 00
35	209 1	182 5	160 2	137 5	6.2	1517	1654	-8 3	9422	54 51	0.2703	41 60
36	209.0	182.4	160 1	137 9	6.5	1427.	1633	-12 6	9316	54.51	0 2544	41.60
37	208.7	182 2	159 9	137 6	6.4	1467.	1644.	-10.7	9337	54.51	0.2615	41 60
38	208.8	182 0	159.6	137.5	6.8	1378	1619.	-14.9	9316.	53.46	0.2455	40 80
39	209.1	184.2	163.8	143.3	6.4	1334.	1640.	-18.6	8563.	50.19	0.2378	38.30
40	208.8	184 2	163.8	143.8	6 4	1315.	1639.	-19 8	8457.	51 50	0.2344	39 30
41	208 5	184.2	163.9	144.0	6.2	1353	1653.	-18 2	8415.	50.71	0.2411	38 70
42	208 3	184 3	164 1	144 1	5 9	1430	1676.	-14 7	8416	50.19	0.2548	38 30
43	209.7	185.8	165,3	145.1	5.6	1527.	1699.	-10.1	8520.	52.42	0.2722	40.00
44	209.3	186.0	165.6	145.3	4.9	1724.	1750.	-1.5	8571.	50.32	0.3072	38.40
45	209 8	184.5	163 8	143.4	6.8	1266.	1617	-21.7	8604.	50.32	0.2256	38.40
46	209 5	184 8	164 2	143 8	6 2	1379.	1653	-16 6	8583.	50 32	0 2458	38 40
47	210 3	190 2	173 7	157 2	5 2	1328	1728	-23 1	6909	41 93	0 2367	32 00
48	209 6	190.2	173 9	158 1	5 0	1345	1746.	-23 0	6719	41.41	0 2397	31 60
49	209.4	190 0	173 4	157.3	4.7	1449.	1770.	-18.2	6845	41.41	0.2582	31 60
50	210.0	189.8	171.5	153 7	4.0	1894.	1846.	2.6	7557.	45.08	0 3375	34.40
51	209.5	189.8	171.6	154 0	3.6	2057	1889.	8 9	7494	45.08	0.3666	34.40
52	209 3	189 6	171 4	153 7	3 6	2099	1897	10 7	7515	44 55	0 3742	34 00

STATION NUMBER 3

0.02400 0.03350 -0.01130

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
13	210 8	179 7	152.9	124.0	8.3	1353.	1363.	-0.7	11213.	95.18	0.2412	44.70
14	210.0	178.9	152.3	123 2	8.2	1367.	1367.	0.0	11216.	95.18	0.2436	44.70
15	210.1	179 3	152 4	121.2	6.6	1778	1443.	23.2	11711.	95.82	0 3169	45 00
16	210 0	177 4	151 1	119 9	8 5	1363	1354	0 6	11594	94 76	0 2428	44 50
17	209 5	177 2	150 8	120 6	8 8	1298	1344	-3 4	11406	95 18	0 2313	44 70
18	209 4	177 0	150 6	120 1	8 7	1317	1347	-2 2	11468	73 46	0 2347	34 50
19	210.2	178.6	152.5	122.1	8 0	1418	1374.	3.2	11389.	100.08	0.2528	47.00
20	209 7	178 4	151 8	121 0	7 4	1566.	1403.	11 6	11569.	100.72	0.2791	47.30
21	210 5	178.5	151 9	121.1	8.1	1430.	1372.	4 3	11569	95.82	0 2549	45 00
22	210 1	178 3	151 6	120 8	7 9	1473	1381	6 7	11589	94 76	0 2625	44 50
23	209 9	178 5	151 8	121 5	7 8	1479	1385	6 7	11485	93 69	0 2636	44 00
24	210 0	178 9	153 1	123 4	8 0	1396	1375.	1 6	11185	93 69	0 2489	44 00
25	209.7	178.0	152.5	123.0	8 8	1261.	1343.	-6.1	11086.	90.29	0.2247	42 40
26	209 5	178 2	152.6	123.0	8 3	1338	1362.	-1 7	11126.	89.43	0 2386	42.00
27	210.0	178.1	152.7	122 9	8 8	1260	1342.	-6.1	11128	90.29	0 2245	42.40
28	211 0	179 6	154 9	126 1	9 1	1188	1333	-10 8	10785	92 63	0 2118	43.50
29	210 7	179 8	154 8	125 9	8 5	1285	1357	-5 3	10864	93 69	0 2290	44 00
30	210 4	179 8	155 0	126 1	8 2	1321	1367	-3 4	10825	91 14	0 2354	42 80
31	211.0	179.9	155.0	126.1	8.7	1250.	1348.	-7.3	10844.	90.29	0.2228	42.40
32	210 7	179.9	155.0	126.0	8.3	1307.	1362.	-4.1	10865.	89.43	0.2329	42 00
33	210.4	179 7	154.9	126.0	8.3	1305.	1363.	-4.3	10825.	90.29	0.2326	42.40
34	209 5	179.4	155 3	127 5	8.5	1231	1355	-9 1	10460.	87 31	0 2194	41 00
35	209 1	179.5	155 5	127.8	8 1	1290.	1372	-6.0	10420.	88.58	0 2299	41 60
36	209 0	179 5	155 6	128 0	8 1	1288	1373.	-6 2	10380	88 58	0 2295	41 60
37	208.6	178.8	154 9	127.3	8.4	1242.	1360.	-8.7	10380.	88.58	0.2213	41.60
38	208.7	178.8	155.1	127.5	8.5	1217.	1355.	-10.2	10341.	86.88	0.2168	40.80
39	209.0	180 9	158 7	132.9	8.1	1196.	1372.	-12.8	9675.	81.56	0.2132	38.30
40	208 7	181.0	159.0	133 6	8.0	1199.	1377	-12 9	9553	83 69	0 2137	39.30
41	208.4	181.0	159.0	133.4	7.5	1271	1395	-8.9	9595.	82.41	0.2266	38 70
42	208.2	181.0	159.1	133 8	7 5	1260.	1395.	-9.7	9513.	81.56	0.2246	38 30
43	209.7	181.9	160.1	134.4	7.9	1208.	1378.	-12.4	9577.	85.18	0.2153	40.00
44	209.2	182.0	160.0	134.4	7.3	1306.	1405.	-7.0	9595.	81.77	0.2328	38.40
45	209.8	181.7	159.5	133.7	8.1	1196.	1372.	-12.8	9675.	81.77	0.2133	38.40
46	209.5	181 9	159 8	134 3	7.8	1232	1385	-11 0	9594.	81.77	0 2196	38 40
47	210 2	188 1	170 6	150 3	6.3	1200	1457.	-17 6	7619	68 14	0 2140	32 00
48	209 6	188.2	171.0	150 7	5 7	1325	1496.	-11 4	7561.	67.29	0 2361	31.60
49	209.4	187.9	170.3	149.9	5.7	1352.	1499.	-9.8	7659.	67.29	0.2409	31.60
50	209.9	186.8	167.8	145.7	6.0	1390.	1480.	-6.1	8285.	73.25	0.2477	34.40
51	209.4	186.7	167.8	145 9	5.7	1443.	1496.	-3.6	8224.	73.25	0 2571	34.40
52	209 2	186 5	167 5	145 4	5 6	1490	1506	-1 0	8285	72 40	0 2656	34 00

STATION NUMBER 4

0.01440 0.02290 0.00190

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
13	210.8	175 9	149.7	120.6	9.5	1222.	1214.	0.7	11652.	131.79	0.2179	44.70
14	210.0	175.1	149.1	119.8	9.5	1232.	1216.	1 3	11654	131.79	0.2196	44.70
15	210.1	175 3	149.8	119.7	9.0	1305.	1232.	5.9	11722	132.68	0.2326	45.00
16	210 1	174 0	149 0	118 9	10 4	1116	1187	-6 0	11619	131 20	0 1988	44 50
17	209 7	173 5	148 8	118 5	10 5	1108	1186	-6 6	11600.	131 79	0 1975	44 70
18	209 5	173 4	148 7	118 4	10 4	1119	1189	-5.9	11600	101 72	0 1994	34 50
19	210.2	175.5	150.7	120.7	9 1	1266.	1227.	3.2	11556.	138.57	0 2256	47.00
20	209.9	175.0	150.2	120 0	9 2	1260	1224.	2 9	11599.	139.46	0.2246	47.30
21	210.5	175.5	150.4	120.0	9 1	1286.	1228.	4 8	11704.	132.68	0.2293	45.00
22	210 2	175 0	150 0	119 6	9 3	1253	1220	2 7	11683	131 20	0.2233	44 50
23	210 0	174 9	150 0	119 3	9 1	1294	1229	5 3	11727	129.73	0 2307	44 00
24	210 0	175 8	151 6	122 3	9 2	1222	1223	-0 1	11282	129 73	0 2178	44 00
25	209.8	175 3	151.0	121.9	9.6	1169.	1211.	-3.5	11260.	125.01	0.2083	42.40
26	209.6	175.1	151 1	122.0	9 7	1153.	1208.	-4 6	11198.	123.83	0.2055	42 00
27	210 2	175.2	151.3	122 0	10 1	1110.	1196.	-7.2	11220.	125.01	0 1978	42.40
28	211 0	177.2	153 3	124 6	9 3	1194	1221	-2 3	11091	128.26	0 2127	43 50
29	210.8	177.1	153 6	124 8	9 2	1194	1223	-2 4	11030	129 73	0 2129	44 00
30	210.4	176 9	153 3	124 6	9 1	1216	1229	-1 1	11029	126 19	0 2167	42 80
31	211.0	177.6	154 2	125.5	9.0	1218.	1230.	-1.0	10988.	125.01	0.2170	42.40
32	210.7	177.5	154.1	125.4	8 8	1245.	1237.	0.6	10988.	123.83	0.2219	42 00
33	210.5	177.3	154.1	125.2	8.8	1256.	1240.	1.3	10990.	125.01	0 2238	42.40
34	209 5	176 6	153 7	126 1	9 4	1138	1219	-6 7	10649	120 88	0 2029	41 00
35	209 1	176.5	153 8	126 0	9 0	1186.	1232	-3 7	10651.	122.65	0 2114	41 60
36	209 0	176 3	153 6	125 8	9 1	1173	1229	-4 5	10651	122.65	0 2090	41 60
37	208.7	175.6	152.8	125.3	9.6	1100.	1210.	-9.1	10607.	122.65	0.1960	41.60
38	208.7	175.7	153.1	125.7	9 7	1091.	1210.	-9 8	10544.	120.29	0.1945	40.80
39	209.0	178.0	156 6	130.9	9.1	1097.	1229.	-10.8	9932.	112.92	0.1955	38.30
40	208 8	177 6	156 3	130 6	9 3	1068	1222.	-12.6	9911.	115 87	0.1903	39 30
41	208.5	177 6	156 4	130 7	9.0	1098	1231	-10 8	9890.	114.10	0.1957	38.70
42	208.3	177.4	156.3	130.4	8 9	1113.	1234.	-9.8	9913.	112.92	0.1983	38.30
43	209.7	179.2	157.5	132.4	8.9	1114.	1236.	-9.9	9865.	117.94	0.1985	40.00
44	209.2	178.9	157.7	132.1	8.5	1165.	1250.	-6.8	9869.	113.22	0.2076	38.40
45	209.8	179.4	158.0	132.4	8.5	1163.	1248.	-6.8	9910.	113.22	0.2073	38.40
46	209 5	179 2	158.0	132 2	8.3	1188.	1255	-5.3	9912.	113 22	0.2117	38.40
47	210.3	186.5	169.5	149.4	6.6	1191.	1332.	-10.6	7822.	94 35	0 2123	32 00
48	209.6	186.1	169.5	149.5	6.4	1199.	1338	-10 4	7718	93.17	0.2137	31 60
49	209.4	185.6	169.0	148.7	6.5	1189.	1333.	-10.8	7782.	93.17	0.2119	31.60
50	209.9	184.7	166.3	144.7	6.6	1269.	1328.	-4.4	8433.	101.42	0.2261	34.40
51	209.5	184 2	166.1	144.1	6.6	1287.	1331.	-3.4	8456.	101.42	0.2293	34.40
52	209 2	183.9	165 8	143 7	6 5	1303	1335.	-2.4	8478	100.25	0 2322	34 00

STATION NUMBER 5

0.03230 0.02560 0.00080

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
13	210 8	174.4	138.6	110 1	11.7	1111.	1084.	2.5	13044	168.40	0 1980	44.70
14	210 0	173.7	138.0	109 7	11.8	1102.	1083.	1.7	12983.	168 40	0.1964	44.70
15	210.1	173.8	137.9	109.3	11.6	1132.	1088.	4.0	13084.	169.53	0.2017	45.00
16	210 1	172 6	136 7	108 3	12 9	1013	1060	-4 4	13043	167 65	0 1805	44 50
17	209 8	172 1	136 4	108 1	13 2	985	1053	-6 5	12983	168 40	0 1755	44 70
18	209.7	172 0	136 2	107 7	13 0	1000	1056	-5 3	13044	129 98	0 1782	34 50
19	210 2	170.4	137.8	109.4	15 9	777.	1005.	-22.7	12380.	177.07	0.1386	47.00
20	209.9	173.3	138 1	109.2	11.8	1098.	1082.	1.5	13005.	178.20	0.1957	47 30
21	210.5	173.6	137.8	109 3	12.2	1065.	1073.	-0.7	13044	169.53	0.1899	45.00
22	210 2	173 3	137 6	108 6	12 0	1096	1079	1 6	13126	167 65	0 1954	44 50
23	210 1	173 2	137.7	108 4	11 8	1110	1082	2 6	13148.	165 77	0 1978	44 00
24	210 0	174 6	140 2	112 3	11 4	1108	1092	1 5	12639	165 77	0 1975	44 00
25	209.8	174.1	139.7	111.7	11.7	1087.	1086.	0.0	12660.	159.74	0.1937	42.40
26	209.7	173 9	139 8	111.8	11.8	1066.	1082	-1.5	12600.	158 23	0.1900	42.00
27	210 2	174 1	139.9	112 0	12.2	1037.	1075.	-3.6	12599.	159.74	0.1848	42.40
28	211 0	175 5	142 0	114 8	12 1	1016	1076	-5 5	12315.	163 88	0 1811	43 50
29	210 7	175 5	142 0	114 5	11 6	1063.	1086	-2 2	12376	165.77	0 1894	44 00
30	210 4	175 4	142 0	114.5	11 5	1078	1090	-1 2	12356	161 24	0 1921	42.80
31	211.0	176.3	142 7	115.1	11.1	1122.	1100.	2.0	12417.	159.74	0.2000	42.40
32	210 7	176.3	143 0	115 3	10.8	1149.	1107.	3.7	12377.	158.23	0.2047	42.00
33	210 5	176.0	142.6	115 0	10.9	1135.	1104.	2.8	12377.	159.74	0.2022	42.40
34	209 5	175.7	143 2	116 4	10 9	1106	1105	0 1	12032	154 46	0 1971	41 00
35	209 1	175 4	143 2	116 2	10 7	1120.	1109.	1.0	12013	156 72	0.1995	41.60
36	209.1	175 4	143.0	116.0	10 7	1128.	1110	1 7	12053.	156.72	0.2011	41 60
37	208.7	174.6	142.3	115.6	11.3	1061.	1095.	-3.1	11971.	156.72	0.1891	41.60
38	208.8	174.7	142.4	115.8	11.3	1054.	1094.	-3.6	11950.	153.71	0.1878	40.80
39	209,0	176.4	145.7	120.7	11.1	1015.	1099.	-7.6	11301.	144.29	0.1810	38.30
40	208.6	176 0	145 2	120.0	11.0	1034.	1102.	-6.2	11362.	148.06	0 1842	39,30
41	208.9	176.2	145.6	120.2	11.0	1031.	1101.	-6.4	11363.	145.80	0.1838	38.70
42	208.3	176.1	145.5	120 2	10.6	1072.	1112.	-3.6	11342.	144.29	0.1911	38.30
43	209.6	177.6	146.9	121.9	10.5	1073.	1114.	-3.6	11301.	150.70	0.1913	40.00
44	209.2	177.3	146.8	121.6	10.4	1091.	1118.	-2.4	11301.	144.67	0.1944	38.40
45	209.8	178.4	147.8	122.7	9.9	1142.	1131.	1.0	11301.	144.67	0.2036	38.40
46	209.5	178 3	147.8	122 4	9.5	1188.	1141.	4.1	11342.	144 67	0.2118	38 40
47	210.2	186.0	162.2	143.0	7.7	1139.	1205.	-5.5	8723.	120.56	0.2029	32.00
48	209 6	185.7	162.2	142 8	7 3	1190.	1219	-2.4	8704.	119.05	0.2121	31 60
49	209.3	185.1	161.5	141.9	7.5	1173.	1213.	-3.3	8765.	119.05	0.2090	31.60
50	209 9	184.0	158.3	137.1	7.8	1225.	1201.	2.0	9516.	129.60	0.2183	34.40
51	209 5	183.7	158.1	136.9	7.7	1234.	1204.	2.5	9496.	129.60	0.2200	34.40
52	209 2	183 3	157 7	136 4	7.7	1230.	1203	2 3	9516	128 09	0.2193	34 00

APPENDIX D

TOLUENE CONDENSATION

Sample Calculations

Sample Run #60

Toluene Properties

	Vapor	Liquid
k Btu/hr•ft•°F		0.065
ρ lb/ft^3		48.07
λ Btu/lb	158	
μ lb/hr•ft		0.5566
Cp Btu/lb•°F		0.44

SS 304 thermal conductivity = 9.0 Btu/hr•ft•°F

Station #2

Location	Displacement (inch)	Temperature (°F)
Vapor	-	226.7
Front	0.0144	189.1
Middle	0.0144	175.4
Back	-0.0013	161.8

Best fit straight line for the temperature gradient through the SS 304 plate:

$y = A_0 + A_1 x$

$y \equiv$ temperature, °F

$x \equiv$ distance from front surface, inch

x	y
0.25 - 0.0144	189.1
0.5 - 0.0144	175.4
0.75 + 0.0013	161.8

$\Sigma\, xy = 251.29$ $\qquad \Sigma\, y = 526.3$

$\Sigma\, x = 1.4725$ $\qquad \Sigma\, x^2 = 0.8558$

$\Sigma i = 3$

$$A_1 = \frac{\Sigma\, xy * \Sigma\, i - \Sigma\, y * \Sigma\, x}{\Sigma\, i * \Sigma\, x^2 - \Sigma\, x * \Sigma\, x} = -52.92$$

$$A_0 = \frac{\Sigma\, y - A_1\ \Sigma\, x}{\Sigma\, i} = 201.41$$

At the front surface, x = 0

$T_s = 201.4 - 52.92 * x$

$= 201.4$

ΔT across the condensate

$= T_v - T_s$

$= 226.7 - 201.4$

$= 25.3$

Heat flux through the SS 304 plate

$$\frac{Q}{A} = K \frac{\Delta T}{\Delta x}$$

$$= \frac{9.0 * [201.41 - (201.41 - 52.92 * 1)]}{1/12}$$

$$= 5715 \text{ Btu/hr-ft}^2$$

Condensing heat transfer coefficient

$$h = \frac{Q/A}{\Delta T} = \frac{5715}{25.3}$$

$$= 226 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

Prediction based on Nusselt's equation

$$h = \left[\frac{k_l^3\ \rho_l^2\ \ g\lambda}{4\ \mu_l\ (T_v - T_s)\ x}\right]^{1/4} * \left[1 + 0.68\ \frac{Cp_l(\ T_v - T_s)}{\lambda}\right]^{1/4}$$

$$= \left[\frac{0.065^3 * 48.07^2 * 32 * 3600^2 * 158}{4 * 0.5566 * 25.3 * 8/12}\right]^{1/4}$$

$$* \left[1 + 0.68 * \frac{0.44 * 25.3}{158}\right]^{1/4}$$

$= 185$ Btu/hr•ft^2•^{0}F

$$\%\ \text{Error} = \frac{226 - 185}{185} * 100$$

$= 22.2\%$

Condensate Reynolds number and condensation number

Condensate rate = 205 ml/min

$$= 205 * \frac{1}{1000} * \frac{1}{28.32} * 60 * 48.07$$

$$\frac{ml}{min} * \frac{lit}{ml} * \frac{ft^3}{lit} * \frac{min}{hr} * \frac{lb}{ft^3}$$

$= 20.88$ lb/hr

Condensate loading

$$\Gamma = \frac{\text{condensate rate}}{\text{perimeter}}$$

$$= \frac{20.88}{2/12} = 125.28\ \text{lb/hr•ft}$$

Local condensate Reynolds number

$$= \frac{4\Gamma}{\mu_l}$$

$$= \frac{4 * 125.28 * 8/26}{0.5566}$$

$$= 277$$

Local condensation number

$$= h \left[\frac{k_l^3 \; \rho_l^2 \; g}{\mu_l^2}\right]^{-1/3}$$

$$= 0.2386$$

SOURCE CODE

```
$JOB
C23456789
      DIMENSION T(70,20),NRUN(70),DLOC(5),NV(5),NF(5),NM(5),NB(5)
      DIMENSION XT(3,5),C(3),D(3)
      DIMENSION XP(25),YP(25),XPP(125),YPP(125),W1(25),W2(25)
      DATA KW,KXYP/6,0/
      DATA NV/1,17,18,19,20/
      DATA NF/16,5,7,14,13/
      DATA NM/2,4,8,10,11/
      DATA NB/3,6,9,12,15/
      DATA DLOC/3.,8.0,13.0,18.0,23.0/
      DATA XT/0.016,0.0151,0.0123,0.0144,0.0144,-0.0013,0.024,0.0335,-0.
     #0113,0.0144,0.0229,0.0019,0.0323,0.0256,0.0008/
C     DATA XT/15*0.0/
      DATA LF/11/
      MPT=0
10    K=MPT+1
      READ(5,*,END= 99)NRUN(K)
      MPT=MPT+1
      READ(5,*) (T(MPT,I),I=2,10)
      READ(5,*) (T(MPT,I),I=11,20)
      READ(5,*)W1(MPT),W2(MPT)
      T(MPT,1)=(T(MPT,17)+T(MPT,18)+T(MPT,19)+T(MPT,20))/4.0
      GO TO 10
99    HN=688.05
      C(1)=0.25
      C(2)=0.5
      C(3)=0.75
      DO 60 NST=1,5
      J1=NV(NST)
      J2=NF(NST)
      J3=NM(NST)
      J4=NB(NST)
      WRITE(6,21)
 21   FORMAT(1H1,//////,'   ')
      WRITE(6,20)NST,(XT(J,NST),J=1,3)
20    FORMAT(18X,' STATION NUMBER',I3,/,13X,3F10.5,//,
     #8X,'RUN',1X,' TV   ','  TF   ','  TM   ','  TB   ',2X,'DT',5X,
     #'H',5X,'HNU',5X,'% ERR',4X,'Q/A',7X,'X',7X,'Y',5X,'ML/M',/)
      DO 40 I=1,MPT
      SYXW=0.0
      SY=0.0
      SI=3
      SXW=0.0
      SXWXW=0.0
      D(1)=T(I,J2)
      D(2)=T(I,J3)
      D(3)=T(I,J4)
      DO 30 J=1,3
      SYXW=SYXW+D(J)*(C(J)-XT(J,NST))
      SY=SY+D(J)
      SXW=SXW+C(J)-XT(J,NST)
30    SXWXW=SXWXW+(C(J)-XT(J,NST))**2
      A1=(SYXW*SI-SY*SXW)/(SI*SXWXW-SXW*SXW)
      A0=(SY-A1*SXW)/SI
      DT=T(I,J1)-A0
      Q=-A1*108.0
      H=-A1*108.0/DT
      HNU=HN/(DLOC(NST)*DT)**0.25
      HNU=HNU*(1.0+0.68*0.44*DT/158.0)**0.25
      PCER=(H-HNU)/HNU*100.0
      YP(I)=H/947.08
      XP(I)=W1(I)*DLOC(NST)/5.921
      WRITE(LF,210)XP(I),YP(I)
210   FORMAT(1X,F10.5,2X,F8.4)
      WRITE(6,50)NRUN(I),T(I,J1),T(I,J2),T(I,J3),T(I,J4),DT,H,HNU,PCER,Q
     @,XP(I),YP(I),W1(I)
40    CONTINUE
 50   FORMAT(8X,I2,4(1X,F5.1),1X,F5.1,2(1X,F6.0),2X,F7.1,2X,F7.0,2X,F6.1
     #,2X,F6.4,2X,F6.2)
      WRITE(LF,220)
220   FORMAT(1X,'   ')
```

```
60     CONTINUE
       WRITE(6,21)
       STOP
       END
$ENTRY
54
160.3,142.4,154.2,172.8,135.5,167.0,147.8,128.8,143.3
132.3,122.2,155.7,160.4,112.2,178.9,227.8,227.3,227.5,227.4
256.5,53.1
55
160.0,141.9,154.1,172.7,135.3,166.9,147.8,129.0,143.4
132.3,122.1,155.7,160.3,112.0,178.4,227.3,226.8,227.1,227.1
260.0,63.0
56
160.1,142.1,154.6,173.1,136.0,167.2,148.0,129.1,143.5
132.2,122.0,155.6,160.2,112.0,178.0,226.9,226.5,226.8,226.8
255.0,66.7
57
159.8,141.7,153.7,172.5,134.7,166.7,147.5,128.2,143.2
132.0,121.9,155.7,160.6,112.1,178.7,227.8,227.4,227.7,227.6
265.0,57.5
58
159.5,141.3,153.9,172.6,134.8,167.0,147.5,128.2,143.5
132.3,121.9,155.9,160.5,112.0,178.0,227.4,227.0,227.3,227.3
255.0,75.0
59
181.2,168.4,176.0,189.5,162.7,185.0,170.7,155.9,166.3
156.5,150.1,174.5,179.1,140.9,193.9,226.8,226.6,226.8,226.9
210.0,142.5
60
180.7,167.4,175.4,189.1,161.8,184.2,169.6,154.8,165.5
155.9,149.4,173.9,178.3,140.2,193.4,226.7,226.5,226.7,226.8
205.0,145.4
61
187.8,175.8,182.7,195.0,170.6,190.8,178.0,163.3,174.0
165.4,159.4,181.8,185.7,157.5,199.9,228.6,228.4,228.7,228.8
220.0,290.0
62
188.0,175.9,182.9,195.2,170.8,191.0,178.2,163.5,174.5
166.0,160.1,182.2,186.0,152.0,199.9,228.2,228.1,228.3,228.4
200.0,305.0
63
188.3,176.6,183.3,195.4,171.2,191.4,178.6,163.9,179.6
166.0,159.8,182.2,185.9,151.8,199.9,228.0,227.9,228.1,228.3
205.0,300.0
64
184.5,171.7,179.2,192.3,166.2,188.3,174.4,158.7,170.5
160.7,154.9,178.5,183.2,145.4,197.9,228.7,228.5,228.7,228.8
215.0,280.0
65
185.7,173.3,180.3,193.1,167.6,189.5,176.0,160.7,172.5
163.9,157.3,181.0,184.8,149.5,198.8,228.8,228.6,228.9,229.0
212.0,285.0
66
188.6,176.9,183.5,195.7,171.7,191.9,179.1,164.4,175.5
167.1,160.9,183.3,186.9,153.1,200.5,228.4,228.2,228.5,228.6
200.0,290.0
67
162.4,144.0,155.3,174.0,136.4,169.0,149.4,128.6,146.0
134.6,123.9,158.2,162.9,114.1,181.5,228.3,228.0,228.4,228.5
270.0,235.0
68
184.8,173.2,180.6,192.5,168.4,188.1,175.3,160.6,170.1
158.2,155.6,173.2,181.3,145.4,195.9,226.7,226.2,226.4,226.0
190.0,30.0
69
160.2,142.1,154.1,172.7,135.2,167.4,148.1,127.2,144.1
132.7,122.5,155.9,160.7,112.8,178.9,227.3,226.8,227.3,227.4
245.0,80.0
70
185.7,173.4,180.7,193.4,168.2,189.4,176.0,160.7,172.3
162.7,157.1,179.9,184.2,148.0,198.1,228.1,227.9,228.1,228.2
```

```
210.0,285.0
71
162.6,143.8,155.3,174.1,136.5,169.1,149.7,128.7,146.2
133.8,124.1,157.6,163.2,113.4,181.6,228.4,228.2,228.6,228.6
270.0,260.0
72
169.6,153.1,162.5,179.5,145.4,173.7,155.6,136.1,150.8
138.0,129.8,161.0,166.7,118.0,186.5,228.3,228.1,228.4,228.5
260.0,260.0
73
172.5,156.4,166.1,182.3,149.7,176.3,159.1,140.4,153.7
140.9,133.6,163.3,169.1,121.5,188.6,228.2,228.0,228.3,228.3
250.0,255.0
$IBSYS
```

RESULTS

Nomenclature for Data Printout

TV	vapor temperature, °F
TF	front thermocouple, °F
TM	middle thermocouple, °F
TB	back thermocouple, °F
DT	ΔT_f, °F
H	condensing coefficient, Btu/hr•ft^2•°F
HNU	H calculated by Nusselt equation
%ERR	(H - HNU)/HNU * 100
Q/A	local heat flux, Btu/hr•ft^2
X	local condensate Reynolds number
Y	local condensation number
ML/M	condensate volumetric flow rate, ml/min

STATION NUMBER 1

0.01600 0 01510 0.01230

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
54	227.5	178.9	160.3	142.4	31.8	246.	223.	10.2	7826	130 0	0 2600	256.50
55	227.1	178.4	160.0	141.9	31.8	246.	223.	10.2	7826.	131.7	0.2599	260.00
56	226.7	178.0	160.1	142.1	32 1	240	223.	7.6	7697.	129 2	0.2534	255.00
57	227 6	178 7	159 8	141 7	31 9	249	223	11 4	7933	134 3	0 2626	265 00
58	227 2	178 0	159 5	141 3	32 3	244	223	9 5	7869	129 2	0.2574	255 00
59	226 8	193 9	181 2	168 4	21 0	260	247	5 5	5467	106.4	0 2745	210 00
60	226.7	193.4	180 7	167.4	21.1	264.	246.	7.2	5575.	103.9	0.2788	205.00
61	228.6	199 9	187 8	175 8	17.6	294.	257.	14.3	5167.	111.5	0.3107	220.00
62	228 2	199.9	188.0	175.9	17.2	299.	259.	15.7	5146.	101.3	0 3162	200.00
63	228 1	199 9	188 3	176 6	17 3	288	258	11 5	4996	103 9	0 3040	205 00
64	228 7	197 9	184 5	171 7	18 7	300	254.	18 3	5617	108 9	0 3168	215 00
65	228 8	198 8	185 7	173 3	18 3	299	255	17 1	5467	107.4	0.3152	212 00
66	228.4	200 5	188 6	176.9	17.0	297.	259.	14.6	5060	101 3	0 3141	200.00
67	228.3	181.5	162.4	144.0	29.5	272	227.	19 8	8040.	136.8	0.2876	270.00
68	226 3	195.9	184.8	173.2	19 8	246.	250.	-1.8	4867	96.3	0 2594	190.00
69	227 2	178 9	160 2	142 1	31 3	252	224	12 3	7890	124 1	0 2659	245 00
70	228 1	198 1	185 7	173 4	18 5	286	254	12 4	5296	106 4	0 3017	210 00
71	228 4	181 6	162 6	143 8	29 3	276	228	21 3	8105	136 8	0 2916	270 00
72	228.3	186.5	169.6	153.1	26.4	271.	233.	16 2	7161.	131.7	0 2864	260.00
73	228.2	188.6	172.5	156.4	24.7	280.	237.	18.0	6904.	126.7	0.2956	250.00

STATION NUMBER 2

0.01440 0 01440 -0.00130

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
54	227.8	172 8	154.2	135 5	38 1	205.	168.	22.2	7809.	346.6	0 2162	256.50
55	227.3	172.7	154 1	135 3	37 7	208.	168	23 7	7830.	351.3	0.2194	260 00
56	226 9	173 1	154 6	136.0	37 0	210	169.	24.3	7767.	344 5	0.2215	255.00
57	227 8	172 5	153 7	134 7	38 2	207	167	23 7	7914	358 0	0 2188	265 00
58	227 4	172 6	153 9	134 8	37 7	210	168	25 1	7915	344 5	0 2219	255 00
59	226 8	189 5	176 0	162 7	25 2	222	185	20 4	5610	283 7	0 2347	210 00
60	226.7	189.1	175 4	161.8	25.3	226.	185.	22.4	5715.	277 0	0.2386	205.00
61	228.6	195.0	182 7	170 6	22 6	226.	190.	19 1	5108.	297.2	0.2384	220.00
62	228 2	195.2	182.9	170 8	22.0	232	191.	21.6	5108.	270 2	0 2449	200.00
63	228 0	195 4	183 3	171 2	21 7	234	192	22 0	5066	277 0	0 2468	205 00
64	228 7	192 3	179 2	166 2	24 6	222	186	19 4	5464	290 5	0 2342	215 00
65	228 8	193 1	180 3	167 6	24 2	221	187	18 2	5338	286 4	0 2329	212 00
66	228.4	195.7	183.5	171 7	21 9	229.	191.	19 9	5024	270 2	0 2418	200.00
67	228 3	174 0	155 3	136.4	37.3	211.	168.	25 4	7872	364.8	0.2229	270.00
68	226 7	192 5	180 6	168 4	23.3	217.	188.	15.2	5046	256 7	0 2290	190.00
69	227 3	172 7	154 1	135 2	37 6	209	168	24 2	7852	331 0	0 2204	245 00
70	228 1	193 4	180 7	168 2	23 4	226	188	20 1	5276	283.7	0 2385	210 00
71	228 4	174 1	155 3	136 5	37 3	211	168	25 3	7872	364 8	0 2227	270 00
72	228.3	179.5	162 5	145.4	33.4	214.	173.	23.7	7139.	351.3	0.2258	260.00
73	228 2	182.3	166 1	149.7	31.1	219.	176.	24 7	6826.	337.8	0.2314	250.00

STATION NUMBER 3

0.02400 0.03350 -0.01130

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
54	227.3	167.0	147 8	128.8	45 0	171.	143.	19.5	7679	563 2	0 1803	256.50
55	226 8	166 9	147 8	129 0	44 7	170.	143.	19 1	7618.	570 8	0.1799	260.00
56	226.5	167.2	148 0	129.1	44 0	174	144.	21.2	7658.	559 9	0 1836	255.00
57	227 4	166 7	147 5	128 2	45 2	171	143	20 1	7741	581 8	0 1809	265 00
58	227 0	167 0	147 5	128 2	44 4	176	143	22 6	7800	559 9	0 1853	255 00
59	226 6	185 0	170 7	155 9	29 8	196	157	24 9	5854	461 1	0 2074	210 00
60	226.5	184.2	169 6	154 8	30.4	194.	156.	24.2	5912.	450.1	0.2051	205 00
61	228 4	190 8	178 0	163.3	26.2	212.	162.	30 6	5542.	483.0	0 2236	220 00
62	228 1	191.0	178 2	163 5	25 7	216.	163.	32 5	5542	439.1	0 2280	200 00
63	227 9	191 4	178 6	163 9	25 1	221	164	35 0	5542	450 1	0 2334	205 00
64	228 5	188 3	174 4	158 7	27 9	213	160	33 7	5964	472 0	0 2254	215 00
65	228 6	189 5	176 0	160 7	27 2	214	161	32 9	5803	465 5	0 2256	212 00
66	228 2	191.9	179 1	164 4	24 9	223.	164.	35 8	5542	439 1	0 2353	200.00
67	228.0	169 0	149 4	128.6	42.5	191.	145.	32 2	8131.	592 8	0.2019	270.00
68	226 2	188 1	175 3	160 6	26 7	208	161.	28 7	5542	417 2	0.2194	190 00
69	226 8	167 4	148 1	127 2	42 9	189	144	30 6	8093	537 9	0 1991	245 00
70	227 9	189 4	176 0	160 7	26 6	218	162	34 7	5783	461 1	0 2297	210 00
71	228 2	169 1	149 7	128 7	42 5	191	145	32 2	8134	592 8	0 2019	270 00
72	228.1	173.7	155.6	136 1	39.0	194.	148.	31 5	7569.	570.8	0.2049	260.00
73	228.0	176.3	159.1	140 4	37 0	196.	149	30 8	7228.	548.9	0.2065	250 00

STATION NUMBER 4

0 01440 0 02290 0 00190

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
54	227.5	160 4	143.3	122 2	49.2	164.	129.	27 0	8057.	779 8	0 1729	256 50
55	227.1	160.3	143.4	122.1	48 8	165.	129.	27.7	8059.	790 4	0.1742	260 00
56	226 8	160.2	143 5	122.0	48.6	166.	129.	28.3	8060	775.2	0.1753	255.00
57	227 7	160 6	143 2	121 9	49 0	167	129	29 0	8162	805 6	0 1759	265 00
58	227 3	160 5	143 5	121 9	48 6	168	129	29 5	8144	775 2	0 1769	255 00
59	226 8	179 1	166 3	150 1	34 0	180	140	27 9	6118	638 4	0 1897	210 00
60	226 7	178 3	165 5	149 4	34 8	175	140	25 3	6096	623 2	0 1849	205.00
61	228.7	185.7	174.0	159 4	30.7	181.	144.	25.7	5548.	668 8	0 1911	220.00
62	228 3	186 0	174.5	160 1	30 1	181	145.	25 4	5463	608 0	0 1914	200.00
63	228 1	185 9	179 6	159 8	28 0	198	147	34 8	5548	623 2	0 2093	205 00
64	228 7	183 2	170 5	154 9	32 3	185	142	30 1	5969	653 6	0 1954	215 00
65	228 9	184 8	172 5	157 3	31 2	186	143	29 6	5800	644 5	0 1962	212 00
66	228.5	186.9	175.5	160.9	29.3	187	145.	28 5	5486.	608.0	0 1975	200.00
67	228 4	162.9	146 0	123.9	47 0	175.	130	34 3	8230.	820 8	0.1848	270 00
68	226 4	181 3	170 1	155 6	32 9	165	142.	16 3	5423.	577.6	0.1738	190.00
69	227 3	160 7	144 1	122 5	48 5	166	129	28 4	8061	744 8	0 1754	245 00
70	228 1	184 2	172 3	157 1	31 1	184	143	28 1	5718	638 4	0 1940	210 00
71	228 6	163 2	146.2	124 1	46 9	176	130	34 9	8251	820 8	0 1858	270 00
72	228 4	166 7	150.8	129.8	44 2	176.	132	33.3	7788.	790.4	0.1861	260.00
73	228.3	169.1	153 7	133 6	42.4	177.	133	32 4	7492.	760.0	0 1866	250.00

STATION NUMBER 5
0.03230 0.02560 0.00080

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
54	227.4	155.7	132.3	112.2	54.7	161.	118.	36.2	8828.	996.4	0 1703	256.50
55	227 1	155.7	132.3	112.0	54 3	163.	119.	37.7	8869.	1010.0	0.1724	260.00
56	226.8	155.6	132 2	112 0	54 2	163	119.	37.6	8849.	990 5	0.1725	255 00
57	227.6	155 7	132 0	112 1	55 0	161	118	36 1	8847	1029 4	0 1699	265 00
58	227 3	155.9	132 3	112 0	54 3	164	119	38 4	8909	990 5	0 1733	255 00
59	226 9	174 5	156 5	140 9	39 3	174	128.	35 9	6819	815 7	0 1834	210 00
60	226.8	173.9	155 9	140.2	39 7	172.	127.	35 2	6840.	796 3	0.1819	205.00
61	228.8	181.8	165.4	157.5	38.7	127.	128.	-0.9	4916.	854.6	0.1341	220.00
62	228 4	182.2	166 0	152 0	34 4	178.	132.	35 2	6129	776.9	0 1881	200 00
63	228 3	182 2	166 0	151 8	34 2	180	132	36 7	6170	796 3	0 1906	205 00
64	228 8	178 5	160 7	145 4	37 4	180	129	39 0	6717	835 2	0 1897	215 00
65	229 0	181 0	163 9	149 5	35 8	179	131	36 8	6392	823 5	0 1887	212 00
66	228.6	183.3	167.1	153 1	33.5	183	133.	37.9	6129	776.9	0.1932	200 00
67	228.5	158.2	134 6	114.1	53 1	169.	119	41.5	8950.	1048.8	0.1781	270.00
68	226 0	173.2	158 2	145.4	42.0	134.	126.	6.8	5642.	738.1	0 1419	190.00
69	227 4	155 9	132 7	112 8	54 7	160	118	35 1	8747	951 7	0 1689	245 00
70	228 2	179 9	162 7	148 0	35 9	180	131.	38 3	6474	815 7	0 1906	210 00
71	228 6	157 6	133 8	113 4	53 8	167	119.	40 3	8970	1048 8	0 1762	270 00
72	228.5	161 0	138.0	118.0	50 7	172	120.	42.9	8727.	1010.0	0.1818	260.00
73	228.3	163.3	140.9	121.5	48.7	174.	122.	43.4	8483.	971.1	0.1841	250 00

APPENDIX E

TOLUENE-WATER MIXTURE CONDENSATION

Sample Calculations

Sample Run #110

Toluene and Water Properties

	Water		Toluene	
	Vapor	Liquid	Vapor	Liquid
k Btu/hr•ft•°F		0.3845		0.067
ρ lb/ft^3	0.0199	60.73	0.2146	50.0
λ Btu/lb	988		168	
μ lb/hr•ft		0.896		0.7139
Cp Btu/lb•°F		1.0		0.425

SS 304 thermal conductivity = 9.0 Btu/hr•ft•°F

Station #4

Location	Displacement (inch)	Temperature (°F)
Vapor	-	184.7
Front	0.0144	153.5
Middle	0.0229	139.7
Back	0.0019	123.1

Test cell condensation rate

Toluene: 57.5 ml/min

Water: 16.0 ml/min

Auxiliary condenser condensation rate

Toluene: 176.5 ml/min

Water: 46.0 ml/min

Mixture properties evaluation

Condensation rates

Toluene: 57.5 ml/min

$$= 57.5 * \frac{1}{1000} * \frac{1}{28.32} * 60 * 50$$

$$\frac{\text{ml}}{\text{min}} * \frac{\text{lit}}{\text{ml}} * \frac{\text{ft}^3}{\text{lit}} * \frac{\text{min}}{\text{hr}} * \frac{\text{lb}}{\text{ft}^3}$$

= 6.091 lb/hr

Water: 16 ml/min

$$= 16 * \frac{1}{1000} * \frac{1}{28.32} * 60 * 60.73$$

$$\frac{\text{ml}}{\text{min}} * \frac{\text{lit}}{\text{ml}} * \frac{\text{ft}^3}{\text{lit}} * \frac{\text{min}}{\text{hr}} * \frac{\text{lb}}{\text{ft}^3}$$

= 2.059 lb/hr

Mixture thermal conductivity K_l

$$k_l = \frac{w_w k_w + w_o k_o}{w_w + w_o}$$

$$= \frac{2.059 * 0.3845 + 6.091 * 0.067}{2.058 + 6.091}$$

$$= 0.1472 \text{ Btu/hr·ft·}^0\text{F}$$

Mixture vapor density

$$\rho_v = \frac{w_w + w_o}{\frac{w_w}{\rho_{v_w}} + \frac{w_o}{\rho_{v_o}}}$$

$$= \frac{2.059 + 6.091}{\frac{2.059}{0.0199} + \frac{6.091}{0.2146}}$$

$$= 0.0618 \text{ lb/ft}^3$$

Mixture liquid density

$$\rho_l = \frac{\rho_{l_w} v_w + \rho_{l_o} v_o}{v_w + v_o}$$

$$= \frac{60.73 * 16.0 + 50.0 * 57.5}{16.0 + 57.5}$$

$$= 52.34 \text{ lb/ft}^3$$

Mixture liquid viscosity

$$\mu_l = \frac{w_w + w_o}{\frac{w_w}{\mu_{l_w}} + \frac{w_o}{\mu_{l_o}}}$$

$$= \frac{2.059 + 6.091}{\frac{2.059}{0.896} + \frac{6.091}{0.7139}}$$

$$= 0.7525 \text{ lb/hr·ft}$$

Mixture liquid specific heat

$$Cp_l = \frac{w_w \; Cp_{lw} + w_o \; Cp_{lo}}{w_w + w_o}$$

$$= \frac{2.059 * 1 + 6.091 * 0.425}{2.059 + 6.091}$$

$$= 0.5703 \text{ Btu/lb}\cdot{}^0\text{F}$$

Best fit straight line for the temperature gradient through the SS 304 plate:

$y = A_0 + A_1 \; x$

$y \equiv$ temperature, °F

$x \equiv$ distance from front surface, inch

x	y
0.25 - 0.0144	153.5
0.5 - 0.0229	139.7
0.75 + 0.0019	123.1

$\Sigma \; xy = 194.91$ $\Sigma \; y = 416.3$

$\Sigma \; x = 1.4608$ $\Sigma \; x^2 = 0.8428$

$\Sigma i = 3$

$$A_1 = \frac{\Sigma \; x \; y * \Sigma \; i - \Sigma y * \Sigma \; x}{\Sigma \; i * \Sigma \; x^2 - \Sigma \; x * \Sigma \; x} = -59.36$$

$$A_0 = \frac{\Sigma \; y - A_1 \; \Sigma \; x}{\Sigma \; i} = 167.67$$

At the front surface, $x = 0$

$$T_s = 167.67 - 59.36 * x$$

$$= 167.67°F$$

ΔT across the condensate

$$= T_v - T_s$$

$$= 184.7 - 167.67$$

$$= 17.0°F$$

Heat flux through the SS 304 plate

$$\frac{Q}{A} = K \frac{\Delta T}{\Delta x}$$

$$= \frac{9.0 * [167.67 - (167.67 - 59.36 * 1)]}{1/12}$$

$$= 6411 \text{ Btu/hr} \cdot \text{ft}^2$$

Condensing heat transfer coefficient

$$h = \frac{Q/A}{\Delta T} = \frac{6411}{17}$$

$$= 377 \text{ Btu/hr} \cdot \text{ft}^2 \cdot {}^0\text{F}$$

Prediction based on Bernhardt's equation

$$h_o = [\frac{k_{lo}^3 \rho_{lo}^2 g \lambda_o}{4\mu_{lo}(T_v - T_s) x}]^{1/4} * [1 + 0.68 \frac{Cp_{lo} (T_v - T_s)}{\lambda_o}]^{1/4}$$

$$= [\frac{0.067^3 * 50^2 * 32 * 3600^2 * 168}{4 * 0.7139 * 17 * 18/12}]^{1/4}$$

$$* [1 + 0.68 * \frac{0.425 * 17}{168}]^{1/4}$$

$$= 164.96 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

$$h_w = [\frac{k_{lw}^3 \rho_{lw}^2 g \lambda_w}{4 \mu_{lw} (T_v - T_s) x}]^{1/4} * [1 + 0.68 \frac{Cp_{lo} (T_v - T_s)}{\lambda_w}]^{1/4}$$

$$= [\frac{0.3845^3 * 60.73^2 * 32 * 3600^2 * 988}{4 * 0.898 * 17 * 18/12}]^{1/4}$$

$$* [1 * 0.68 * \frac{1 * 17}{988}]^{1/4}$$

$$= 986.96 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

$$h_{NU} = \frac{h_o v_o + h_w v_w}{v_o + v_w}$$

$$= \frac{164.96 * 57.5 + 986.96 * 16.0}{57.5 + 16.0}$$

$$= 344 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

Vapor velocity calculation

Total mass flowrate for toluene

$$= (57.5 + 176.5) * \frac{60}{1000} * \frac{50}{28.32}$$

$$= 24.79 \text{ lb/hr}$$

Total mass flowrate for water

$$= (16 + 46) * \frac{60}{1000} * \frac{60.73}{28.32}$$

= 7.98 lb/hr

Local toluene vapor flowrate

$$= \frac{[176.5 + 57.5 * (1 - 18/26)] * 50 * 60}{1000 * 28.32}$$

= 20.57 lb/hr

Local water vapor flowrate

$$= \frac{[46 + 16 * (1 - 18/26)] * 60.73 * 60}{1000 * 28.32}$$

= 6.55 lb/hr

Vapor channel cross section: 2" x 1 1/8"

Local vapor velocity

$$= \frac{20.57/0.2146 + 6.55/0.0199}{3600 * (2 * 1.125)/144}$$

= 7.56 ft/sec

Prediction based on Boyko-Kruzhilin equation

Total mass velocity G_T

$$= \frac{24.79 + 7.98}{2 * 1.125} * 144$$

$= 2097.3\ lb/hr \cdot ft^2$

Equivalent diameter for vapor flow channel

$$D_{eq} = 4 * \frac{C.S.\ Area}{perimeter}$$

$$= 4 * \frac{2 * 1.125}{(2 + 1.125) * 2}$$

= 1.44 inch

Total condensate Reynolds number

$$Re_T = \frac{G_T\ D_{eq}}{\mu_l}$$

$$= \frac{2097.3 * 1.44/12}{0.7525}$$

$$= 334.5$$

Condensate Prandtl number

$$Pr_l = \frac{Cp_l\ \mu_l}{k_l}$$

$$= \frac{0.5703 * 0.7525}{0.1472}$$

$$= 2.9154$$

Local quality

$$x = \frac{6.55 + 20.57}{7.98 + 24.79}$$

$$= 0.8276 \equiv 82.76\%$$

$$h_{BK} = \frac{k_l}{D_{eq}} * 0.024 * Re_T^{0.8} * Pr_l^{0.43} * [1 * \frac{\rho_l - \rho_v}{\rho_v} x]^{1/2}$$

$$= \frac{0.1472}{1.44/12} * 0.024 * 334.5^{0.8} * 2.9154^{0.43}$$

$$* [1 + \frac{52.34 - 0.0618}{0.0618} * 0.8276]^{1/2}$$

$$= 129.2\ Btu/hr \cdot ft^2 \cdot {}^0F$$

Prediction based on Akers-Turner equation 1

Toluene condensing heat load

$$Q_o = \frac{6.091 * 168}{26 * 2/144} = 2631 \text{ Btu/hr}\cdot\text{ft}^2$$

Water condensing heat load

$$Q_w = \frac{2.059 * 988}{26 * 2/144} = 5231 \text{ Btu/hr}\cdot\text{ft}^2$$

Total condensing heat load

$$= 7862 \text{ Btu/hr}\cdot\text{ft}^2$$

Condensing heat transfer coefficient

$$H_{AT1} = \frac{Q_o\ h_o + Q_w\ h_w}{Q_o + Q_w}$$

$$= \frac{2631 * 164.96 + 5231 * 986.96}{7862}$$

$$= 712 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

Prediction based on Akers-Turner equation 2

Local condensate loading

$$\Gamma = \frac{(6.091 + 2.059) * 18/26}{2/12}$$

$$= 33.85 \text{ lb/hr}\cdot\text{ft}$$

Weight averaged mixture liquid density

$$\rho_l = \frac{w_w\ \rho_{lw} + w_o\ \rho_{lo}}{w_w + w_o}$$

$$= \frac{2.059 * 60.73 + 6.091 * 50}{2.059 + 6.091}$$

$$= 52.71 \text{ lb/ft}^3$$

Condensing heat tranfer coefficient

$$h_{AT2} = 1.47 \left(\frac{4\Gamma}{\mu_o}\right)^{-1/3} \left(\frac{k_1^3 \rho_1^2 g}{\mu_o^2}\right)^{1/3}$$

$$= 1.47 \left(\frac{4 * 33.85}{0.7139}\right)^{-1/3} * \left(\frac{0.1472^3 * 52.71^2 * 32 * 3600^2}{0.7139^2}\right)^{1/3}$$

$$= 494.3 \ \text{Btu/hr} \cdot \text{ft}^2 \cdot {}^0\text{F}$$

Local condensate Reynolds number

$$= \frac{4\Gamma}{\mu_1}$$

$$= \frac{4 * 33.85}{0.7525}$$

$$= 179.9$$

Local condensation number

$$= h \left[\frac{k_1^3 \rho_1^2 g}{\mu_1^2}\right]^{-1/3}$$

$$= 0.2030$$

SOURCE CODE

```
$JOB
C23456789
      DIMENSION T(70,31),NRUN(70),DLOC(5),NV(5),NF(5),NM(5),NB(5)
      DIMENSION XT(3,5),C(3),D(3),FRLOC(5)
      DIMENSION TOPR(50),WPR(50),TOSE(50),WSE(50),COLPR(50),COLSE(50)
      DIMENSION XPP(200),YPP(200),XP(50),YP(50)
      DATA KW,KXYP/6,0/
      DATA NV/1,17,18,19,20/
      DATA NF/16,5,7,14,13/
      DATA NM/2,4,8,10,11/
      DATA NB/3,6,9,12,15/
      DATA DLOC/3.,8.0,13.0,18.0,23.0/
      DATA XT/0.016,0.0151,0.0123,0.0144,0.0144,-0.0013,0.024,0.0335,-0.
     #0113,0.0144,0.0229,0.0019,0.0323,0.0256,0.0008/
      DATA LF/11/
C     DATA XT/15*0.0/
      DO 90 I=1,5
90    FRLOC(I)=(3.0+(I-1.0)*5.0)/26.0
      MPT=0
10    K=MPT+1
      READ(5,*,END= 99)NRUN(K)
      MPT=MPT+1
      READ(5,*) (T(MPT,I),I=2,10)
      READ(5,*) (T(MPT,I),I=11,20)
      READ(5,*) TOPR(MPT),WPR(MPT),TOSE(MPT),WSE(MPT),COLPR(MPT),COLSE(MP
     #T),T(MPT,28),T(MPT,29),T(MPT,30),T(MPT,31)
      COLSE(MPT)=COLSE(MPT)*2.7/100.
      T(MPT,1)=(T(MPT,17)+T(MPT,18)+T(MPT,19)+T(MPT,20))/4.0
      GO TO 10
99    HNT=685.0
      HNW=4115.9
      C(1)=0.25
      C(2)=0.5
      C(3)=0.75
      DO 100 NST=1,5
      J1=NV(NST)
      J2=NF(NST)
      J3=NM(NST)
      J4=NB(NST)
      WRITE(6,21)
21    FORMAT(1H1,/////,'   ')
      WRITE(6,110)NST,(XT(J,NST),J=1,3)
110   FORMAT(18X,'STATION NUMBER ',I3,/,13X,3F10.5,//,10X,'RUN',3X,
     #'TV',4X,'TF',4X,'TM',4X,'TB',2X,'PRIMARY',25X,'AUXILIARY',/,39X,'T
     #OL',2X,'WAT',5X,'COOLANT ',13X,'TOL',2X,'WAT',9X,'COOLANT',/,
     # 49X,' GPM    IN    OUT',20X,'GPM    IN    OUT',/)
      DO 120 I=1,MPT
 120  WRITE(6,130)NRUN(I),T(I,J1),T(I,J2),T(I,J3),T(I,J4),TOPR(I),WPR(I)
     #,COLPR(I),T(I,28),T(I,29),TOSE(I),WSE(I),COLSE(I),T(I,30),T(I,31)
 130  FORMAT(9X,I3,6(1X,F5.1),1X,F4.2,2(1X,F5.1),5X,2(1X,F5.1),2X,F4.2,2
     #(1X,F5.1))
100   CONTINUE
      DO 60 NST=1,5
      J1=NV(NST)
      J2=NF(NST)
      J3=NM(NST)
      J4=NB(NST)
      WRITE(6,21)
      WRITE(6,20)NST
20    FORMAT(18X,' STATION NUMBER',I3,/,8X,' RUN',2X,'DT',6X,'H',5X
     #,'HNU',5X,'HBK',4X,'Q/A LOC  CONDENS.  ','VAP VEL',5X,'X',6X,'Y
     #',4X,'HAT1',5X,'HAT2',/)
      DO 40 I=1,MPT
      SYXW=0.0
      SY=0.0
      SI=3
      SXW=0.0
      SXWXW=0.0
      D(1)=T(I,J2)
      D(2)=T(I,J3)
      D(3)=T(I,J4)
      DO 30 J=1,3
```

```
      SYXW=SYXW+D(J)*(C(J)-XT(J,NST))
      SY=SY+D(J)
      SXW=SXW+C(J)-XT(J,NST)
30    SXWXW=SXWXW+(C(J)-XT(J,NST))**2
      A1=(SYXW*SI-SY*SXW)/(SI*SXWXW-SXW*SXW)
      A0=(SY-A1*SXW)/SI
      DT=T(I,J1)-A0
      Q=-A1*108.0
      H=-A1*108.0/DT
      HNTOL=HNT*((1.+0.68*0.425*DT/168.)/(DLOC(NST)*DT))**0.25
      HNWAT=HNW*((1.+0.68*DT/988.0)/(DLOC(NST)*DT))**0.25
      HNU=(HNTOL*TOPR(I)+HNWAT*WPR(I))/(TOPR(I)+WPR(I))
C
      TOPRW=TOPR(I)*0.1059
      TOSEW=TOSE(I)*0.1059
      WPRW=WPR(I)*0.1287
      WSEW=WSE(I)*0.1287
      VAPTOL=TOSE(I)+(1.0-FRLOC(NST))*TOPR(I)
      VAPWAT=WSE(I)+(1.0-FRLOC(NST))*WPR(I)
      VAPVEL=(VAPTOL*0.1059*4.66 + VAPWAT*0.1287*50.2)/(3600.0*
     #2.0*1.125/144.0)
      CONDL = (0.067*TOPRW + 0.3845*WPRW) / (TOPRW+WPRW)
C     CONDL=( 0.067*TOPR(I) + 0.3845*WPR(I) )/
C    #( TOPR(I) + WPR(I) )
      VISCL=(TOPRW+WPRW)/( TOPRW/0.7139 + WPRW/0.896 )
      CPL=(TOPRW*0.425+WPRW)/(TOPRW+WPRW)
      RHOV=(TOPRW+WPRW)/(TOPRW*4.66+WPRW*50.2)
      RHOL=(TOPR(I)*50.0+WPR(I)*60.73)/(TOPR(I)+WPR(I))
      RET=(TOPRW+TOSEW+WPRW+WSEW)*1.44/12.0/VISCL*144.0/2.25
      PRL=CPL*VISCL/CONDL
      QUAL=(VAPTOL*0.1059+VAPWAT*0.1287)/(TOPRW+TOSEW+WPRW+WSEW)
      GR3=(1.0+QUAL*(RHOL-RHOV)/RHOV)**0.5
      HBK=0.024*RET**0.8*PRL**0.43*GR3*CONDL/1.44*12.0
      QCON=(TOPR(I)*17.791+WPR(I)*127.2)/56.0*144.0
      HAT1=( HNTOL*TOPR(I)*17.791*(1.0+0.68*0.425*DT/168.0)**0.25 +
     # HNWAT*WPR(I)*127.2*(1.0+0.68*DT/988.0)**0.25 )/QCON/56.0*144.0
      RHOLW = (50.0*TOPRW+60.73*WPRW)/(TOPRW+WPRW)
      ATG1 = 24.0*(WPRW+TOPRW)*FRLOC(NST)/0.7139
      ATG2 = CONDL**3*RHOLW**2*32.0*3600.0**2/0.7139**2
      HAT2 = 1.47*(ATG2/ATG1)**(1./3.)
      YP(I)=H*(VISCL**2/ (CONDL**3*RHOL*(RHOL-RHOV)*32.*3600.*3600.) )**
     #(1.0/3.0)
      XP(I)=(WPRW+TOPRW)*24.0*FRLOC(NST)/VISCL
      WRITE(LF,200) XP(I),YP(I)
200   FORMAT(1X,F10.4,1X,F8.4)
      WRITE(6,50)NRUN(I),DT,H,HNU,HBK,Q,QCON,VAPVEL,XP(I),YP(I),HAT1,
     #HAT2
40    CONTINUE
      WRITE(LF,210)
210   FORMAT('  ')
 50   FORMAT(9X,I3,1X,F5.1,3(1X,F6.0),2(2X,F7.0),5X,F6.2,3X,F6.2,2X,F6.4
     #,3X,F6.0,2X,F6.0)
60    CONTINUE
      WRITE(6,21)
      STOP
      END
$ENTRY
75
129.8,112.2,125.8,145.0,106.3,142.2,121.2,97.8,119.3
108.0,94.8,135.7,139.2,85.1,148.4,183.2,182.8,183.2,182.9
97.5,20.0,140.0,30.0,1.98,46.0,42.4,46.6,42.6,57.8
76
136.0,118.3,130.8,149.4,111.8,145.6,125.7,105.8,124.7
115.5,101.9,140.8,142.4,93.3,153.9,183.8,184.7,183.9,183.7
92.5,20.0,185.0,45.0,2.0,50.0,53.3,57.4,54.0,73.5
77
131.1,111.4,126.9,146.9,106.3,144.4,122.4,100.6,121.1
112.0,96.9,138.0,139.8,89.5,150.6,183.3,184.1,183.0,183.2
90.0,22.5,180.0,42.5,3.0,49.5,52.6,55.5,53.3,72.8
78
127.7,106.7,123.8,145.0,102.0,141.6,119.2,97.1,118.6
110.7,93.9,137.9,138.5,87.8,148.3,183.4,184.1,183.1,183.2
```

95.0,25.0,175.0,45.0,4.0,49.5,53.3,55.5,54.1,72.8
79
137.3,120.1,133.3,150.4,116.0,148.0,130.3,111.1,130.3
122.7,110.5,145.1,147.2,104.1,155.1,184.1,182.6,182.6,182.5
77.5,17.5,172.5,40.0,4.1,48.0,76.8,78.7,77.4,95.5
80
134.6,116.6,131.1,148.8,113.0,146.2,127.7,108.0,128.0
121.0,107.8,143.9,145.6,102.3,152.6,183.2,181.8,181.8,183.0
82.5,17.5,180.0,45.0,5.2,48.0,77.1.78.6,77.8,95.4
81
133.7,115.1,130.1,148.2,111.3,146.2,127.0,106.5,126.3
120.7,106.1,142.7,142.9,101.6,151.7,181.8,181.9,181.6,183.2
81.5,18.5,185.0,25.0,6.0,48.0,77.3,78.6,77.8,95.4
82
139.6,122.5,135.7,153.0,118.3,149.5,132.0,113.1,131.3
123.6,111.5,145.2,147.7,104.9,157.2,185.3,184.5,183.7,184.9
80.0,20.0,215.0,57.5,3.4,49.5,76.5,78.7,77.1,98.8
83
136.8,118.6,133.4,151.5,115.0,147.8,129.5,109.6,129.5
122.2,109.1,145.1,145.9,103.4,154.9,185.6,183.7,183.7,185.0
77.5,18.0,165.0,40.0,4.5,49.0,76.7,78.4,77.3,99.8
84
134.4,115.9,130.4,148.2,112.0,146.6,127.8,107.6,127.9
120.7,107.3,144.0,144.2,102.1,152.8,183.7,182.3,182.0,183.3
82.0,18.5,162.5,38.5,5.5,49.0,77.0,78.3,77.5,95.0
85
141.1,125.4,136.9,152.7,120.9,150.1,133.6,115.4,132.6
125.4,114.0,147.0,148.1,108.1,157.2,184.1,182.3,182.4,183.7
75.0,15.0,142.5,32.5,2.8,49.0,79.5,82.0,80.1,96.6
86
138.8,122.2,134.9,151.7,118.1,149.1,131.8,112.7,130.8
124.0,111.5,145.2,145.8,106.0,155.4,183.7,182.1,182.2,183.4
72.5,17.5,157.5,37.5,3.6,49.5,79.8,81.8,80.4,97.3
87
139.6,122.2,135.2,152.0,118.2,148.7,131.3,112.6,130.0
123.4,111.1,144.7,145.7,105.7,155.1,183.6,181.8,182.2,183.3
75.0,18.5,152.5,35.0,3.6,49.5,79.9,81.8,80.4,97.2
88
137.6,119.6,134.1,151.0,115.5,148.8,130.3,110.3,130.0
122.7,109.9,144.5,146.3,104.4,154.8,185.0,183.3,183.4,184.5
77.5,18.5,225.0,50.0,4.9,50.0,80.1,81.6,80.7,101.6
89
135.6,117.4,131.5,149.2,113.7,146.7,128.3,108.8,127.7
120.7,107.6,143.0,144.3,102.3,153.4,183.9,182.1,182.0,183.4
72.5,20.0,145.0,35.0,4.6,50.0,76.0,77.6,76.4,91.8
90
133.5,115.2,129.9,148.1,111.6,145.3,126.6,107.0,126.2
119.3,105.8,141.5,142.7,101.9,151.6,183.3,181.6,181.6,183.3
70.0,20.0,142.5,37.5,5.7,50.0,76.7,78.0,77.1,92.5
91
138.1,121.1,133.8,150.8,116.7,148.2,130.2,111.3,129.0
121.0,109.1,143.4,145.4,102.6,155.0,183.8,183.1,182.3,183.6
71.5,18.5,150.0,37.5,3.2,49.0,74.1,76.6,74.4,91.0
92
134.8,116.4,131.1,149.1,112.6,146.2,127.4,107.7,127.3
119.3,106.3,142.6,144.1,100.6,152.3,184.1,183.7,182.6,183.8
72.5,19.0,140.0,35.0,4.9,50.0,75.0,76.6,75.0,92.1
93
137.5,119.9,133.5,151.7,115.4,147.2,128.6,109.1,128.4
119.9,107.1,143.8,145.0,100.0,155.9,185.3,184.5,184.6,185.8
80.0,17.5,265.0,40.0,2.8,72.0,67.1,69.9,67.2,82.2
94
135.4,116.7,131.2,149.6,111.9,145.8,126.6,106.1,126.6
117.5,104.4,141.9,144.7,97.6,154.0,185.9,185.0,184.5,185.6
80.0,20.0,225.0,50.0,3.8,71.0,67.4,69.6,67.5,83.0
95
132.1,112.1,128.4,148.2,108.0,144.8,124.3,102.8,124.0
116.3,101.6,141.3,142.0,95.6,151.5,185.9,185.1,184.3,185.3
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96
133.4,112.1,129.9,150.9,108.4,146.7,125.7,122.4,125.7
118.1,103.1,143.4,145.4,96.7,155.5,191.3,190.9,190.1,191.0

87.5,22.5,340.0,80.0,5.5,65.0,65.3,66.9,65.5,96.9
97
134.4,113.8,130.3,150.9,109.6,147.7,126.7,124.5,126.5
117.7,103.3,143.6,145.2,96.8,155.8,190.8,190.4,189.6,190.5
87.5,22.5,325.0,80.0,4.7,62.0,65.1,67.0,65.3,95.7
98
135.0,114.5,131.4,152.1,110.3,147.7,127.0,123.9,126.0
118.1,103.2,143.8,144.3,96.8,156.2,190.1,190.7,190.0,190.9
82.5,20.0,340.0,75.0,4.4,64.0,65.2,67.0,65.2,95.7
99
138.5,119.0,134.4,154.20,114.1,148.9,128.9,126.3,128.0
119.3,105.3,144.4,146.0,98.0,157.3,190.7,190.4,190.0,190.5
87.5,22.5,333.0,82.0,3.2,68.0,65.6,68.2,65.6,94.3
100
133.5,111.9,129.3,150.1,107.6,147.2,125.2,122.8,124.6
115.8,100.8,140.5,143.4,94.4,153.7,190.7,190.2,190.0,189.5,190.3
87.5,25.0,350.0,85.0,5.6,64.0,66.0,67.6,66.1,94.9
101
142.5,124.7,137.6,155.6,118.9,152.1,133.1,111.5,131.3
120.9,109.5,144.8,149.4,100.5,160.2,190.8,190.6,190.0,190.6
85.0,17.5,340.0,80.0,2.3,65.0,64.9,68.5,65.0,93.6
102
137.4,117.8,133.8,153.9,113.3,149.4,128.9,106.6,128.4
118.5,104.8,143.9,146.5,97.3,156.9,190.4,190.1,189.3,190.5
85.0,22.5,325.0,80.0,3.6,63.0,66.0,68.3,66.1,95.7
103
133.8,112.3,129.6,150.3,108.0,148.5,126.3,102.4,125.3
116.7,101.6,142.3,143.9,95.2,154.2,190.2,190.0,189.6,190.6
85.0,22.5,345.0,85.0,5.5,64.0,66.1,67.7,66.2,96.8
104
153.2,141.7,149.8,162.2,137.9,158.9,146.4,131.9,145.7
139.0,131.2,155.7,157.2,125.5,165.3,183.8,183.2,183.6,184.6
51.0,14.0,145.0,35.0,1.98,67.0,103.0,105.7,64.0,77.5
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158.4,148.4,155.1,165.4,144.4,162.6,151.6,138.8,150.9
145.9,139.0,159.8,160.7,134.5,167.9,183.2,183.9,183.7,184.6
45.0,12.5,152.5,37.5,1.88,69.0,116.4,118.8,65.0,78.4
106
155.9,144.5,152.0,163.7,140.0,159.8,147.1,132.5,144.6
137.4,130.0,154.5,155.9,123.4,166.0,184.5,182.7,183.7,184.4
52.5,13.5,150.0,37.5,1.05,69.0,95.7,100.7,65.5,79.0
107
151.9,140.3,147.8,160.7,135.3,156.5,143.1,128.0,141.2
133.1,125.4,152.1,154.0,118.0,164.5,183.0,183.0,183.0,184.2
51.5,15.0,142.5,32.5,0.9,51.0,83.4,89.6,66.0,80.7
108
155.6,145.0,152.0,163.4,140.5,159.5,147.2,133.3,145.2
137.3,131.1,153.5,156.6,124.0,165.9,184.2,183.3,183.1,184.0
50.0,15.0,150.0,35.0,0.9,57.0,96.2,101.6,67.2,81.9
109
158.5,149.0,154.9,165.3,144.3,161.6,150.2,137.3,148.4
141.5,135.4,157.1,159.0,129.0,167.5,184.2,183.3,183.2,184.0
47.5,12.5,140.0,32.5,0.82,57.0,102.5,107.9,66.4,82.1
110
149.5,136.1,145.4,159.7,131.2,156.3,141.3,125.2,139.7
132.1,123.1,151.6,153.5,116.4,163.8,186.5,185.0,184.7,186.2
57.5,16.0,176.5,46.0,1.68,61.0,87.6,91.0,64.8,82.2
111
150.8,137.9,147.2,160.7,133.3,157.3,143.1,127.7,142.1
133.9,125.6,152.3,155.1,118.6,164.0,186.1,185.8,184.7,186.0
57.5,15.0,174.0,45.0,1.97,61.0,93.2,96.3,66.1,83.7
112
151.7,139.0,147.9,161.2,134.6,157.5,143.5,128.4,141.1
134.5,125.6,152.4,153.9,119.8,163.8,184.4,185.0,183.8,185.1
57.5,15.0,170.0,42.5,2.0,60.0,96.8,99.9,66.4,83.2
113
155.6,144.4,152.3,164.1,140.4,160.9,148.3,134.6,146.9
140.5,132.9,155.7,158.0,127.5,166.2,185.3,185.0,184.1,185.3
49.5,13.0,170.0,42.5,1.96,58.0,108.0,110.5,66.7,84.1
114
138.8,121.7,134.3,152.2,116.4,147.4,128.8,110.0,127.4
118.5,106.5,142.1,144.2,98.5,156.1,184.2,182.5,182.6,184.2

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115
134.0,114.0,128.9,149.3,107.9,144.1,122.7,99.7,122.3
112.6,98.9,139.6,140.8,90.5,153.4,187.0,187.6,185.9,186.7
82.5,20.0,223.7,57.3,3.0,62.0,56.4,59.3,56.5,75.5
116
128.3,107.0,124.0,145.7,101.8,139.8,117.3,94.0,117.0
106.6,91.4,135.0,136.9,83.3,150.0,186.2,184.1,184.3,185.6
97.5,22.5,197.6,50.0,3.2,54.0,46.0,48.6,46.2,65.1
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RESULTS

Nomenclature for Data Printout and Results

TV	vapor temperature, °F
TF	front thermocouple, °F
TM	middle thermocouople, °F
TB	back thermocouple, °F
PRIMARY	data for test cell
AUXILIARY	data for auxiliary condenser
TOL	toluene condensate flow rate, ml/min
WAT	water condensate flow rate, ml/min
GPM	coolant flow rate, gal/min
IN	coolant inlet temperature, °F
OUT	coolant outlet temperature, °F
DT	ΔT_f, °F
H	condensing coefficient, Btu/hr-ft^2-°F
HNU	H calculated by Nusselt equation
HBK	H calculated by Boyko-Kruzhilin equation
Q/A LOC	local heat flux, Btu/hr-ft^2
CONDENS	heat flux based on condensate flow rate, Btu/hr-ft^2
VAP VEL	vapor velocity, ft/sec
X	local condensate Reynolds number
Y	local condensation number
HAT1	H calculated by Akers-Turner equation 1
HAT2	H calculated by Akers-Turner equation 2

STATION NUMBER 1

0 01600 0.01510 0.01230

RUN	TV	TF	TM	TB	PRIMARY TOL	PRIMARY WAT	PRIMARY COOLANT GPM	PRIMARY COOLANT IN	PRIMARY COOLANT OUT	AUXILIARY TOL	AUXILIARY WAT	AUXILIARY COOLANT GPM	AUXILIARY COOLANT IN	AUXILIARY COOLANT OUT
75	183 0	148.4	129.8	112.2	97.5	20.0	1.98	42.4	46.6	140.0	30.0	1.24	42 6	57.8
76	184.0	153.9	136.0	118.3	92.5	20.0	2 00	53 3	57.4	185.0	45.0	1 35	54.0	73 5
77	183.4	150 6	131 1	111 4	90 0	22 5	3.00	52 6	55.5	180 0	42 5	1 34	53 3	72 8
78	183 4	148 3	127 7	106 7	95 0	25 0	4 00	53 3	55 5	175 0	45 0	1 34	54 1	72 8
79	182 9	155 1	137 3	120 1	77 5	17 5	4 10	76 8	78 7	172 5	40 0	1 30	77 4	95 5
80	182.4	152 6	134.6	116 6	82.5	17 5	5 20	77.1	78 6	180.0	45.0	1.30	77.8	95.4
81	182.1	151.7	133.7	115.1	81.5	18 5	6.00	77.3	78.6	185.0	25.0	1.30	77.8	95.4
82	184.6	157.2	139.6	122 5	80 0	20.0	3.40	76.5	78 7	215 0	57.5	1.34	77.1	98 8
83	184 5	154.9	136 8	118 6	77 5	18 0	4.50	76 7	78 4	165 0	40 0	1 32	77 3	99 8
84	182 8	152 8	134 4	115 9	82 0	18 5	5 50	77 0	78 3	162 5	38 5	1 32	77 5	95 0
85	183 1	157 2	141 1	125 4	75 0	15 0	2 80	79 5	82 0	142 5	32 5	1 32	80 1	96 6
86	182.8	155 4	138 8	122.2	72.5	17 5	3.60	79.8	81 8	157.5	37.5	1.34	80 4	97.3
87	182.7	155.1	139.6	122 2	75.0	18 5	3.60	79 9	81.8	152.5	35 0	1 34	80 4	97.2
88	184.0	154.8	137 6	119 6	77.5	18.5	4.90	80.1	81 6	225.0	50.0	1.35	80 7	101.6
89	182 8	153 4	135.6	117 4	72 5	20 0	4 60	76 0	77 6	145 0	35 0	1 35	76 4	91 8
90	182 4	151 6	133 5	115 2	70 0	20 0	5 70	76 7	78.0	142 5	37 5	1 35	77 1	92 5
91	183 2	155 0	138 1	121 1	71 5	18 5	3 20	74 1	76 6	150 0	37 5	1 32	74 4	91 0
92	183.5	152.3	134.8	116.4	72.5	19 0	4.90	75.0	76.6	140.0	35.0	1.35	75.0	92 1
93	185.0	155 9	137.5	119 9	80 0	17.5	2.80	67.1	69.9	265.0	40.0	1.94	67 2	82.2
94	185 2	154.0	135.4	116.7	80.0	20.0	3.80	67.4	69.6	225.0	50.0	1.92	67.5	83.0
95	185.1	151 5	132 1	112 1	82 5	21 0	5.20	67 3	69 0	290 0	65.0	1 75	67 4	84 2
96	190.8	155.5	133.4	112 1	87.5	22 5	5.50	65.3	66 9	340.0	80 0	1 75	65 5	96 9
97	190.3	155.8	134 4	113.8	87 5	22 5	4.70	65.1	67 0	325.0	80.0	1 67	65 3	95.7
98	190.4	156.2	135.0	114 5	82.5	20.0	4.40	65.2	67.0	340.0	75.0	1.73	65.2	95.7
99	190.4	157.3	138.5	119.0	87.5	22.5	3.20	65.6	68.2	333 0	82.0	1.84	65.6	94.3
100	190.1	153.7	133 5	111 9	87.5	25.0	5 60	66 0	67.6	350 0	85.0	1.73	66 1	94.9
101	190 5	160 2	142 5	124 7	85 0	17 5	2.30	64 9	68 5	340 0	80 0	1.75	65 0	93.6
102	190 1	156 9	137 4	117 8	85 0	22 5	3 60	66 0	68 3	325 0	80 0	1 70	66 1	95 7
103	190.1	154.2	133 8	112 3	85.0	22 5	5 50	66 1	67.7	345.0	85 0	1.73	66 2	96.8
104	183.8	165.3	153.2	141.7	51.0	14.0	1.98	103.0	105 7	145.0	35.0	1 81	64.0	77.5
105	183 8	167.9	158 4	148.4	45.0	12 5	1.88	116.4	118.8	152.5	37 5	1.86	65.0	78 4
106	183.8	166.0	155.9	144 5	52.5	13.5	1.05	95.7	100.7	150.0	37.5	1.86	65 5	79.0
107	183 3	164.5	151 9	140 3	51 5	15 0	0 90	83 4	89 6	142 5	32 5	1 38	66 0	80.7
108	183 6	165.9	155 6	145 0	50.0	15 0	0 90	96 2	101 6	150 0	35 0	1.54	67 2	81 9
109	183 7	167 5	158.5	149.0	47 5	12.5	0.82	102 5	107 9	140 0	32 5	1 54	66 4	82 1
110	185.6	163.8	149.5	136.1	57.5	16.0	1.68	87.6	91.0	176.5	46.0	1.65	64.8	82.2
111	185.6	164.0	150.8	137.9	57.5	15.0	1.97	93.2	96.3	174.0	45.0	1.65	66.1	83.7
112	184.6	163 8	151.7	139 0	57.5	15 0	2.00	96.8	99.9	170 0	42.5	1.62	66.4	83.2
113	184 9	166 2	155 6	144 4	49 5	13 0	1 96	108 0	110 5	170 0	42 5	1 57	66 7	84 1
114	183.4	156.1	138.8	121 7	71 5	18 5	1.96	62 9	66 7	155 0	38.5	1 84	62 7	76 2
115	186 8	153 4	134 0	114 0	82.5	20 0	3 00	56 4	59 3	223 7	57 3	1 67	56 5	75 5
116	185.0	150.0	128.3	107.0	97.5	22.5	3 20	46.0	48 6	197.6	50.0	1.46	46.2	65.1

STATION NUMBER 2

0.01440 0.01440 -0.00130

RUN	TV	TF	TM	TB	PRIMARY					AUXILIARY				
							COOLANT						COOLANT	
					TOL	WAT	GPM	IN	OUT	TOL	WAT	GPM	IN	OUT
75	183.2	145.0	125.8	106.3	97.5	20.0	1.98	42.4	46.6	140.0	30.0	1.24	42.6	57.8
76	183.8	149.4	130 8	111 8	92.5	20.0	2.00	53.3	57.4	185.0	45.0	1.35	54.0	73.5
77	183 3	146 9	126 9	106 3	90.0	22 5	3 00	52 6	55 5	180 0	42 5	1 34	53 3	72 8
78	183 4	145 0	123 8	102 0	95.0	25 0	4 00	53 3	55.5	175 0	45.0	1 34	54 1	72 8
79	184 1	150 4	133 3	116 0	77.5	17 5	4 10	76 8	78 7	172 5	40 0	1 30	77 4	95 5
80	183.2	148.8	131.1	113.0	82.5	17.5	5.20	77.1	78.6	180.0	45.0	1.30	77 8	95.4
81	181.8	148.2	130.1	111.3	81.5	18.5	6 00	77 3	78 6	185 0	25.0	1 30	77.8	95.4
82	185.3	153.0	135.7	118 3	80.0	20.0	3.40	76.5	78 7	215 0	57.5	1.34	77 1	98.8
83	185 6	151 5	133 4	115 0	77 5	18 0	4 50	76 7	78 4	165 0	40 0	1 32	77 3	99 8
84	183 7	148 2	130 4	112 0	82 0	18 5	5 50	77 0	78 3	162 5	38.5	1 32	77 5	95 0
85	184 1	152 7	136 9	120 9	75 0	15 0	2 80	79 5	82 0	142 5	32 5	1 32	80 1	96 6
86	183.7	151.7	134 9	118.1	72.5	17.5	3.60	79.8	81.8	157 5	37.5	1.34	80.4	97.3
87	183.6	152.0	135 2	118.2	75.0	18 5	3.60	79.9	81.8	152.5	35 0	1 34	80 4	97.2
88	185.0	151 0	134.1	115.5	77 5	18 5	4.90	80.1	81 6	225.0	50.0	1.35	80.7	101.6
89	183 9	149 2	131 5	113 7	72 5	20 0	4 60	76 0	77 6	145 0	35 0	1 35	76 4	91 8
90	183 3	148 1	129 9	111 6	70 0	20 0	5 70	76 7	78 0	142 5	37 5	1 35	77 1	92 5
91	183 8	150 8	133 8	116 7	71 5	18 5	3 20	74 1	76 6	150 0	37 5	1 32	74 4	91 0
92	184 1	149.1	131.1	112 6	72.5	19.0	4.90	75.0	76 6	140.0	35.0	1.35	75 0	92.1
93	185.3	151.7	133.5	115.4	80.0	17.5	2.80	67.1	69.9	265.0	40.0	1.94	67 2	82.2
94	185 9	149.6	131 2	111 9	80.0	20.0	3.80	67.4	69 6	225.0	50.0	1.92	67.5	83 0
95	185 9	148 2	128 4	108 0	82.5	21 0	5 20	67 3	69 0	290 0	65 0	1 75	67 4	84 2
96	191 3	150 9	129 9	108.4	87.5	22 5	5.50	65 3	66.9	340 0	80 0	1.75	65 5	96 9
97	190 8	150 9	130 3	109.6	87.5	22 5	4 70	65 1	67.0	325 0	80 0	1 67	65 3	95.7
98	190.1	152.1	131.4	110.3	82.5	20.0	4.40	65.2	67.0	340.0	75.0	1.73	65.2	95 7
99	190.7	154.2	134.4	114.1	87.5	22.5	3.20	65.6	68.2	333.0	82.0	1.84	65.6	94.3
100	190.7	150.1	129.3	107.6	87.5	25.0	5.60	66.0	67.6	350 0	85.0	1 73	66.1	94.9
101	190 8	155.6	137 6	118 9	85 0	17.5	2.30	64 9	68.5	340.0	80 0	1 75	65 0	93.6
102	190 4	153 9	133.8	113.3	85 0	22.5	3.60	66 0	68 3	325.0	80 0	1.70	66 1	95 7
103	190 2	150.3	129.6	108 0	85 0	22 5	5 50	66 1	67.7	345 0	85 0	1 73	66 2	96 8
104	183.8	162.2	149.8	137.9	51.0	14.0	1.98	103 0	105 7	145 0	35.0	1.81	64.0	77.5
105	183 2	165.4	155.1	144.4	45.0	12.5	1 88	116.4	118 8	152.5	37.5	1.86	65.0	78 4
106	184.5	163.7	152.0	140.0	52.5	13.5	1.05	95.7	100.7	150.0	37.5	1.86	65.5	79.0
107	183.0	160.7	147.8	135 3	51.5	15 0	0 90	83.4	89.6	142 5	32.5	1 38	66 0	80 7
108	184.2	163.4	152 0	140 5	50 0	15 0	0.90	96.2	101.6	150.0	35.0	1 54	67.2	81.9
109	184 2	165.3	154.9	144 3	47.5	12 5	0.82	102 5	107 9	140 0	32.5	1.54	66 4	82.1
110	186 5	159.7	145.4	131 2	57.5	16.0	1.68	87.6	91.0	176 5	46.0	1.65	64.8	82.2
111	186.1	160.7	147.2	133.3	57.5	15.0	1.97	93.2	96.3	174.0	45.0	1.65	66.1	83.7
112	184.4	161.2	147 9	134 6	57 5	15.0	2.00	96.8	99.9	170 0	42 5	1.62	66.4	83 2
113	185 3	164 1	152.3	140 4	49 5	13.0	1 96	108 0	110.5	170.0	42 5	1 57	66 7	84.1
114	184 2	152 2	134 3	116.4	71 5	18 5	1 96	62 9	66 7	155 0	38 5	1 84	62 7	76 2
115	187 0	149.3	128 9	107 9	82 5	20 0	3 00	56 4	59.3	223 7	57 3	1.67	56 5	75 5
116	186.2	145.7	124.0	101.8	97.5	22.5	3.20	46.0	48 6	197.6	50.0	1.46	46.2	65.1

STATION NUMBER 3
0.02400 0.03350 -0.01130

RUN	TV	TF	TM	TB	PRIMARY TOL	PRIMARY WAT	PRIMARY COOLANT GPM	PRIMARY COOLANT IN	PRIMARY COOLANT OUT	AUXILIARY TOL	AUXILIARY WAT	AUXILIARY COOLANT GPM	AUXILIARY COOLANT IN	AUXILIARY COOLANT OUT
75	182.8	142.2	121 2	97.8	97.5	20 0	1.98	42.4	46 6	140.0	30.0	1.24	42 6	57 8
76	184.7	145.6	125 7	105.8	92 5	20 0	2 00	53.3	57.4	185.0	45.0	1.35	54.0	73 5
77	184 1	144 4	122 4	100 6	90 0	22 5	3 00	52 6	55 5	180 0	42 5	1 34	53 3	72 8
78	184 1	141.6	119 2	97 1	95 0	25 0	4 00	53 3	55 5	175 0	45 0	1 34	54 1	72 8
79	182.6	148 0	130 3	111 1	77 5	17.5	4 10	76 8	78.7	172 5	40 0	1 30	77 4	95 5
80	181.8	146 2	127.7	108.0	82.5	17 5	5.20	77.1	78 6	180.0	45.0	1.30	77.8	95.4
81	181.9	146.2	127.0	106.5	81.5	18.5	6.00	77.3	78.6	185.0	25.0	1 30	77.8	95.4
82	184.5	149.5	132.0	113 1	80 0	20 0	3.40	76.5	78 7	215.0	57.5	1.34	77.1	98 8
83	183 7	147 8	129 5	109 6	77 5	18 0	4 50	76 7	78 4	165 0	40 0	1 32	77 3	99 8
84	182 3	146 6	127 8	107 6	82 0	18 5	5 50	77 0	78 3	162.5	38 5	1 32	77 5	95 0
85	182 3	150 1	133 6	115 4	75 0	15 0	2 80	79 5	82 0	142 5	32 5	1 32	80 1	96 6
86	182.1	149.1	131.8	112 7	72.5	17.5	3 60	79.8	81 8	157.5	37 5	1.34	80.4	97.3
87	181.8	148 7	131 3	112 6	75.0	18 5	3.60	79.9	81 8	152 5	35.0	1 34	80 4	97.2
88	183.3	148 8	130.3	110 3	77 5	18.5	4 90	80.1	81 6	225 0	50 0	1 35	80.7	101.6
89	182 1	146 7	128 3	108 8	72 5	20 0	4 60	76 0	77 6	145 0	35 0	1 35	76 4	91 8
90	181 6	145 3	126 6	107 0	70 0	20 0	5 70	76 7	78 0	142 5	37 5	1 35	77 1	92 5
91	183 1	148.2	130 2	111 3	71 5	18 5	3 20	74 1	76 6	150 0	37 5	1 32	74 4	91 0
92	183 7	146 2	127.4	107 7	72.5	19 0	4.90	75.0	76 6	140 0	35.0	1.35	75 0	92.1
93	184.5	147.2	128.6	109.1	80.0	17 5	2.80	67.1	69.9	265.0	40.0	1.94	67 2	82.2
94	185.0	145.8	126.6	106 1	80 0	20 0	3 80	67.4	69 6	225.0	50.0	1.92	67 5	83.0
95	185 1	144 8	124 3	102 8	82 5	21 0	5 20	67 3	69 0	290 0	65 0	1 75	67 4	84 2
96	190 9	146 7	125 7	122 4	87 5	22 5	5 50	65 3	66.9	340.0	80.0	1 75	65 5	96 9
97	190 4	147 7	126.7	124 5	87 5	22.5	4 70	65 1	67.0	325 0	80 0	1 67	65 3	95 7
98	190.7	147.7	127.0	123.9	82.5	20.0	4.40	65.2	67.0	340.0	75.0	1.73	65.2	95.7
99	190.4	148.9	128.9	126.3	87.5	22.5	3.20	65 6	68.2	333.0	82.0	1 84	65.6	94.3
100	190 2	147.2	125.2	122 8	87.5	25.0	5.60	66 0	67.6	350.0	85 0	1.73	66.1	94 9
101	190.6	152.1	133.1	111 5	85 0	17 5	2 30	64 9	68 5	340.0	80 0	1 75	65 0	93 6
102	190 1	149 4	128 9	106 6	85 0	22 5	3 60	66 0	68 3	325 0	80 0	1 70	66 1	95 7
103	190 0	148.5	126.3	102 4	85 0	22.5	5.50	66.1	67 7	345 0	85 0	1.73	66.2	96.8
104	183.2	158.9	146.4	131.9	51.0	14.0	1.98	103.0	105.7	145.0	35.0	1.81	64.0	77.5
105	183.9	162.6	151.6	138.8	45.0	12.5	1.88	116 4	118.8	152.5	37.5	1.86	65 0	78.4
106	182 7	159.8	147.1	132 5	52.5	13.5	1.05	95.7	100.7	150.0	37.5	1.86	65.5	79.0
107	183.0	156 5	143.1	128 0	51 5	15.0	0 90	83.4	89 6	142 5	32 5	1 38	66 0	80 7
108	183.3	159.5	147.2	133 3	50 0	15 0	0.90	96 2	101.6	150 0	35.0	1.54	67 2	81 9
109	183.3	161.6	150 2	137 3	47 5	12 5	0 82	102 5	107.9	140 0	32.5	1 54	66 4	82 1
110	185 0	156.3	141.3	125.2	57 5	16 0	1 68	87 6	91 0	176.5	46.0	1 65	64.8	82.2
111	185.8	157.3	143.1	127.7	57.5	15.0	1.97	93.2	96.3	174.0	45.0	1.65	66.1	83.7
112	185.0	157 5	143 5	128 4	57 5	15.0	2 00	96.8	99.9	170 0	42.5	1.62	66 4	83 2
113	185 0	160 9	148 3	134 6	49 5	13 0	1 96	108 0	110 5	170 0	42.5	1 57	66 7	84 1
114	182 5	147 4	128 8	110 0	71.5	18.5	1 96	62 9	66 7	155 0	38 5	1.84	62 7	76 2
115	187 6	144 1	122 7	99 7	82 5	20 0	3 00	56 4	59 3	223.7	57 3	1.67	56 5	75 5
116	184.1	139.8	117.3	94.0	97.5	22.5	3.20	46.0	48 6	197.6	50.0	1.46	46 2	65.1

STATION NUMBER 4

0.01440 0 02290 0.00190

RUN	TV	TF	TM	TB	PRIMARY TOL	PRIMARY WAT	PRIMARY COOLANT GPM	PRIMARY COOLANT IN	PRIMARY COOLANT OUT	AUXILIARY TOL	AUXILIARY WAT	AUXILIARY COOLANT GPM	AUXILIARY COOLANT IN	AUXILIARY COOLANT OUT
75	183 2	139 2	119 3	94 8	97 5	20 0	1 98	42 4	46.6	140 0	30 0	1 24	42 6	57 8
76	183.9	142 4	124 7	101 9	92.5	20.0	2 00	53.3	57.4	185.0	45.0	1.35	54.0	73 5
77	183 0	139 8	121 1	96 9	90 0	22 5	3 00	52 6	55 5	180 0	42 5	1 34	53 3	72 8
78	183 1	138 5	118 6	93 9	95 0	25 0	4 00	53 3	55 5	175 0	45 0	1 34	54 1	72 8
79	182 6	147 2	130 3	110 5	77 5	17 5	4 10	76 8	78 7	172 5	40 0	1 30	77 4	95 5
80	181.8	145 6	128.0	107 8	82 5	17 5	5.20	77 1	78 6	180 0	45.0	1.30	77 8	95 4
81	181.6	142.9	126.3	106 1	81.5	18.5	6.00	77.3	78.6	185.0	25.0	1.30	77.8	95.4
82	183.7	147.7	131.3	111 5	80.0	20 0	3 40	76 5	78.7	215.0	57.5	1.34	77 1	98 8
83	183 7	145 9	129 5	109 1	77 5	18 0	4 50	76 7	78 4	165 0	40 0	1 32	77 3	99 8
84	182 0	144 2	127 9	107 3	82 0	18 5	5 50	77 0	78 3	162 5	38 5	1 32	77 5	95 0
85	182 4	148 1	132 6	114 0	75 0	15 0	2 80	79 5	82 0	142 5	32 5	1 32	80 1	96 6
86	182.2	145 8	130.8	111.5	72.5	17.5	3.60	79.8	81 8	157.5	37.5	1.34	80.4	97 3
87	182 2	145.7	130 0	111 1	75 0	18.5	3 60	79 9	81 8	152.5	35 0	1 34	80 4	97 2
88	183.4	146 3	130 0	109 9	77.5	18 5	4 90	80.1	81.6	225 0	50 0	1.35	80 7	101 6
89	182 0	144 3	127 7	107 6	72 5	20 0	4 60	76 0	77 6	145 0	35 0	1 35	76 4	91 8
90	181 6	142 7	126 2	105 8	70 0	20 0	5 70	76 7	78 0	142 5	37 5	1 35	77 1	92 5
91	182 3	145 4	129 0	109 1	71 5	18 5	3 20	74 1	76 6	150 0	37 5	1 32	74 4	91 0
92	182.6	144.1	127 3	106 3	72 5	19 0	4.90	75 0	76 6	140.0	35.0	1 35	75.0	92.1
93	184.6	145.0	128.4	107 1	80.0	17.5	2.80	67.1	69.9	265.0	40.0	1.94	67.2	82 2
94	184.5	144.7	126.6	104.4	80 0	20.0	3 80	67.4	69 6	225.0	50.0	1.92	67.5	83.0
95	184 3	142 0	124.0	101 6	82 5	21 0	5 20	67.3	69 0	290 0	65 0	1 75	67 4	84 2
96	190 1	145 4	125 7	103.1	87 5	22 5	5.50	65.3	66.9	340.0	80.0	1.75	65 5	96 9
97	189 6	145.2	126 5	103.3	87 5	22.5	4 70	65 1	67.0	325 0	80 0	1 67	65.3	95 7
98	190.0	144.3	126.0	103.2	82.5	20.0	4.40	65.2	67.0	340.0	75.0	1.73	65.2	95.7
99	190.0	146.0	128 0	105.3	87.5	22.5	3.20	65.6	68.2	333.0	82.0	1.84	65 6	94.3
100	190.0	143.4	124.6	100.8	87.5	25 0	5.60	66.0	67.6	350.0	85.0	1.73	66.1	94.9
101	190 0	149 4	131 3	109 5	85 0	17 5	2 30	64 9	68 5	340.0	80 0	1 75	65 0	93 6
102	189 3	146 5	128 4	104 8	85 0	22 5	3 60	66 0	68 3	325 0	80 0	1 70	66 1	95 7
103	189 6	143.9	125 3	101 6	85 0	22 5	5 50	66 1	67.7	345 0	85 0	1 73	66 2	96 8
104	183 6	157.2	145.7	131 2	51.0	14 0	1.98	103.0	105 7	145 0	35 0	1 81	64.0	77.5
105	183.7	160.7	150.9	139 0	45.0	12.5	1.88	116.4	118 8	152.5	37.5	1.86	65.0	78.4
106	183.7	155.9	144.6	130 0	52.5	13 5	1.05	95 7	100.7	150.0	37.5	1.86	65.5	79.0
107	183 0	154 0	141 2	125 4	51 5	15 0	0 90	83 4	89 6	142 5	32 5	1 38	66 0	80 7
108	183 1	156 6	145 2	131.1	50.0	15.0	0 90	96 2	101 6	150.0	35.0	1 54	67 2	81.9
109	183 2	159 0	148.4	135 4	47 5	12 5	0 82	102.5	107 9	140 0	32.5	1.54	66 4	82 1
110	184.7	153.5	139.7	123 1	57.5	16 0	1.68	87.6	91.0	176.5	46.0	1.65	64.8	82.2
111	184.7	155.1	142.1	125.6	57 5	15.0	1.97	93 2	96.3	174.0	45.0	1.65	66.1	83.7
112	183.8	153.9	141 1	125 6	57.5	15.0	2 00	96.8	99.9	170.0	42.5	1.62	66.4	83.2
113	184 1	158 0	146 9	132 9	49 5	13 0	1 96	108 0	110 5	170.0	42 5	1 57	66 7	84 1
114	182.6	144 2	127 4	106 5	71 5	18 5	1 96	62 9	66 7	155 0	38 5	1 84	62 7	76 2
115	185.9	140 8	122 3	98 9	82 5	20 0	3 00	56 4	59 3	223 7	57 3	1 67	56 5	75 5
116	184.3	136.9	117.0	91.4	97.5	22.5	3.20	46.0	48 6	197.6	50.0	1.46	46 2	65.1

STATION NUMBER 5

O 03230 O.02560 O 00080

RUN	TV	TF	TM	TB	PRIMARY TOL	PRIMARY WAT	PRIMARY COOLANT GPM	PRIMARY COOLANT IN	PRIMARY COOLANT OUT	AUXILIARY TOL	AUXILIARY WAT	AUXILIARY COOLANT GPM	AUXILIARY COOLANT IN	AUXILIARY COOLANT OUT
75	182.9	135.7	108.0	85 1	97.5	20 0	1 98	42.4	46 6	140.0	30 0	1.24	42 6	57.8
76	183 7	140 8	115 5	93 3	92 5	20 0	2.00	53.3	57.4	185.0	45.0	1.35	54.0	73 5
77	183 2	138 0	112 0	89 5	90 0	22 5	3 00	52 6	55 5	180 0	42 5	1 34	53 3	72 8
78	183 2	137 9	110 7	87 8	95 0	25 0	4 00	53 3	55 5	175 0	45.0	1 34	54 1	72 8
79	182 5	145 1	122 7	104 1	77 5	17 5	4 10	76 8	78 7	172 5	40 0	1 30	77 4	95 5
80	183.0	143 9	121.0	102 3	82 5	17 5	5.20	77.1	78 6	180.0	45 0	1.30	77 8	95 4
81	183.2	142 7	120.7	101 6	81 5	18 5	6.00	77 3	78.6	185.0	25.0	1 30	77 8	95.4
82	184.9	145 2	123 6	104 9	80 0	20 0	3 40	76.5	78 7	215 0	57.5	1 34	77 1	98 8
83	185 0	145 1	122 2	103 4	77 5	18 0	4 50	76 7	78 4	165 0	40 0	1 32	77 3	99.8
84	183 3	144 0	120 7	102 1	82 0	18 5	5 50	77 0	78 3	162 5	38 5	1 32	77 5	95 0
85	183 7	147 0	125 4	108 1	75 0	15 0	2 80	79 5	82 0	142 5	32 5	1 32	80 1	96 6
86	183.4	145 2	124.0	106.0	72.5	17.5	3 60	79.8	81 8	157.5	37.5	1.34	80.4	97.3
87	183.3	144 7	123.4	105 7	75.0	18 5	3 60	79 9	81.8	152.5	35 0	1 34	80.4	97 2
88	184.5	144 5	122 7	104 4	77 5	18 5	4.90	80 1	81 6	225.0	50.0	1.35	80 7	101 6
89	183 4	143 0	120 7	102 3	72 5	20 0	4 60	76 0	77 6	145 0	35 0	1 35	76 4	91 8
90	183 3	141 5	119 3	101 9	70 0	20 0	5 70	76 7	78 0	142 5	37 5	1 35	77 1	92 5
91	183 6	143 4	121 0	102 6	71 5	18 5	3 20	74 1	76 6	150 0	37 5	1 32	74 4	91 0
92	183.8	142.6	119.3	100.6	72.5	19.0	4.90	75.0	76.6	140.0	35 0	1.35	75.0	92.1
93	185.8	143.8	119.9	100.0	80.0	17.5	2.80	67.1	69.9	265.0	40.0	1 94	67 2	82.2
94	185 6	141 9	117.5	97 6	80.0	20 0	3.80	67.4	69 6	225 0	50.0	1.92	67 5	83.0
95	185 3	141 3	116 3	95 6	82 5	21 0	5 20	67 3	69 0	290 0	65 0	1.75	67 4	84 2
96	191 0	143 4	118 1	96 7	87 5	22 5	5.50	65 3	66 9	340 0	80 0	1 75	65 5	96 9
97	190 5	143 6	117 7	96 8	87 5	22.5	4 70	65.1	67 0	325 0	80 0	1 67	65 3	95 7
98	190.9	143.8	118.1	96 8	82.5	20.0	4 40	65.2	67.0	340.0	75.0	1.73	65.2	95.7
99	190.5	144.4	119 3	98 0	87.5	22.5	3.20	65.6	68 2	333 0	82.0	1.84	65.6	94.3
100	189.5	140 5	115.8	94.4	87.5	25.0	5 60	66.0	67.6	350 0	85 0	1.73	66.1	94.9
101	190 6	144 8	120 9	100 5	85 0	17 5	2 30	64 9	68 5	340 0	80.0	1 75	65 0	93 6
102	190 5	143 9	118 5	97 3	85 0	22 5	3 60	66 0	68 3	325 0	80 0	1 70	66 1	95 7
103	190 6	142 3	116 7	95 2	85 0	22 5	5 50	66 1	67 7	345 0	85 0	1 73	66 2	96 8
104	184.6	155.7	139.0	125.5	51.0	14.0	1.98	103 0	105.7	145.0	35.0	1.81	64.0	77.5
105	184.6	159.8	145.9	134.5	45.0	12.5	1.88	116.4	118.8	152.5	37.5	1.86	65.0	78.4
106	184.4	154.5	137.4	123.4	52.5	13.5	1.05	95.7	100.7	150.0	37.5	1 86	65.5	79.0
107	184 2	152 1	133 1	118 0	51 5	15 0	0 90	83.4	89 6	142 5	32 5	1 38	66 0	80 7
108	184 0	153 5	137 3	124 0	50 0	15 0	0 90	96 2	101 6	150 0	35 0	1 54	67 2	81 9
109	184 0	157 1	141 5	129 0	47 5	12 5	0 82	102 5	107 9	140 0	32 5	1 54	66 4	82 1
110	186.2	151 6	132.1	116.4	57.5	16 0	1,68	87.6	91.0	176.5	46.0	1 65	64 8	82 2
111	186.0	152.3	133.9	118.6	57.5	15.0	1 97	93 2	96.3	174.0	45.0	1.65	66.1	83.7
112	185.1	152.4	134.5	119.8	57.5	15.0	2.00	96.8	99.9	170.0	42.5	1.62	66.4	83.2
113	185.3	155 7	140 5	127 5	49 5	13 0	1 96	108 0	110 5	170 0	42.5	1.57	66.7	84 1
114	184 2	142 1	118.5	98 5	71.5	18 5	1 96	62.9	66 7	155 0	38 5	1.84	62 7	76 2
115	186.7	139 6	112 6	90 5	82 5	20 0	3 00	56 4	59 3	223 7	57 3	1 67	56 5	75 5
116	185.6	135.0	106.6	83 3	97.5	22.5	3.20	46.0	48 6	197.6	50.0	1.46	46.2	65.1

STATION NUMBER 1

RUN	DT	H	HNU	HBK	Q/A LOC	CONDENS	VAP VEL	X	Y	HAT1	HAT2
75	18 0	431	471	113	7761	11002	7 46	48 01	0 2621	1012	678
76	13 6	559	514	135	7633	10773	9 54	45 95	0 3332	1100	702
77	14 6	576	535	144	8405	11477	9 45	45 92	0 3242	1128	745
78	15.8	565	536	150	8920	12523.	9 98	48 97	0 3114	1122.	745.
79	11.7	641.	543.	127	7504.	9269.	8.49	38.80	0 3751	1157	756
80	13.1	587.	515	128	7719	9498	9.17	40 85	0.3523	1104	725.
81	13 3	588	527	127	7847	9780	7 01	40 84	0 3436	1122	745
82	11 4	653	569	158	7440	10202	11 14	40 82	0 3675	1199	775
83	12 7	611	537	127	7783	9433	8 47	39 00	0 3537	1142	764
84	12.9	614.	530	125.	7912	9802.	8.36	41 04	0.3596	1130.	742.
85	11 2	607.	523.	105	6818	8337.	7.09	36 78	0 3724	1127	733
86	12 0	591.	553.	124	7118	9041.	8.03	36 74	0.3370	1171	791.
87	12 0	586	558	124	7054	9482	7 82	38 17	0 3312	1178	788
88	12 8	590	543	153	7547	9597	10 20	39 19	0 3381	1150	771
89	12 7	609	576	129	7719	9858	7 89	37 74	0 3291	1198	829
90	13.9	560.	571	131	7804.	9744.	8 13	36.71	0 2986	1182.	849
91	12 5	583.	564	127	7268.	9322.	8 06	36.73	0 3237	1183	816.
92	14 4	533.	547	123	7697	9531	7 74	37.34	0.2941	1145	814
93	12 6	613	527	154	7718	9384	9 32	39 82	0 3637	1126	740
94	13 9	574	541	158	7997	10202	10 37	40 82	0 3229	1141	775
95	15 3	553	533	188	8448	10643	12 78	42.24	0 3089	1121	772
96	15 3	607.	535.	213.	9305.	11362	15.14	44.89	0 3377	1123.	760
97	15 2	593	536.	208.	9005.	11362	15 01	44.89	0.3300	1126	760.
98	15.0	596.	525.	202	8941.	10316.	14.27	41.85	0 3394	1111.	759.
99	15 2	540	536	211	8212	11362	15 30	44 89	0 3002	1125	760
100	16 8	534	546	233	8963	12180	16 05	45 89	0 2848	1129	788
101	13 8	551	503	185	7612.	9613	14 61	41.88	0.3345	1081	710
102	15.0	558.	544	211.	8383.	11248	14.99	43.87	0.3068	1137	775
103	16.3	552.	533	219.	8984.	11248.	15.74	43.87	0.3034	1115.	775
104	7.7	661.	652.	119.	5060.	6912.	7.11	26.52	0.3582	1355.	931.
105	6 8	613.	674.	121	4181.	6147	7.26	23.46	0.3305	1399	974
106	7 6	604	635.	118.	4610	6817.	7 40	26 94	0.3359	1333	901
107	7.7	670.	666.	122.	5188	7262	6 91	27.12	0 3545	1372.	947
108	8.0	560	669.	127.	4481.	7194.	7.25	26.51	0.2926	1371.	966
109	7.5	528.	644.	111.	3967.	6262.	6.60	24.48	0.2911	1347.	939.
110	9.1	652.	628.	140.	5939.	7864.	8.90	29.98	0.3515	1303.	898
111	9.6	583	604	133.	5596	7537.	8.67	29.59	0.3225	1265	878
112	9 2	580	611	130	5317	7537	8.34	29.59	0 3207	1279	878
113	8.5	549.	624.	127.	4674.	6517.	8 08	25 50	0.3028	1305	926
114	11.4	650	577.	129.	7376.	9322.	8.22	36 73	0.3605	1211.	815
115	15.0	562.	525.	158.	8448.	10316.	11.22	41.85	0.3202	1111.	759
116	15.2	608.	514	148.	9219.	11820.	10.52	49.00	0.3529	1093.	706.

STATION NUMBER 2

RUN	DT	H	HNU	HBK	Q/A LOC	CONDENS	VAP VEL	X	Y	HAT1	HAT2
75	20 7	392	356	108	8103	11002	6 86	128 02	0 2383	766	489
76	17 4	454	379	130	7873	10773	8 94	122.54	0 2702	812	506
77	18 0	473	398	139.	8501	11477	8 80	122 46	0 2662	839	538
78	18.9	477.	401.	145.	9004.	12523	9 27	130 58	0 2628	840.	537
79	18.1	397.	381.	123.	7202.	9269	7.97	103.46	0.2326	814.	545.
80	18.2	413.	372.	124.	7496.	9498	8.64	108.94	0 2476	798.	523.
81	16 8	459	389	123	7727	9780	6 46	108 90	0 2685	830	537
82	16 6	437	406	153	7265	10202	10 57	108 85	0.2459	855	559
83	17 6	435	389	123	7642	9433	7 94	103 99	0 2519	826	551
84	19 1	398	377.	120.	7580.	9802	7.82	109 45	0.2331	804.	535.
85	17 0	391.	370.	101.	6658.	8337.	6 63	98 07	0 2403	797.	529.
86	16.8	418.	399.	120	7034	9041.	7 52	97 98	0.2384	844.	571
87	16 3	434	405	120	7077	9482	7 28	101 78	0 2454	856	569
88	17 7	421	392	149	7436	9597	9 66	104 52	0 2410	832	556
89	18 7	398	410	125	7432.	9858	7 32	100 63	0 2154	853	598
90	18 7	409.	416.	127.	7642.	9744.	7 57	97.89	0.2178	861	612.
91	17.6	406.	406.	122.	7139.	9322.	7 53	97.95	0.2252	851.	587
92	18.4	415.	403.	119.	7643.	9531	7.20	99 57	0 2288	844.	587.
93	17 2	441	381	150	7599	9384	8 80	106 20	0 2615	816	534
94	19 1	413	392	154	7895	10202	9 79	108 85	0 2322	826	559
95	19 4	433	393	184	8417	10643	12 18	112 65	0 2417	827	557
96	21.1	421.	387.	208.	8899	11362.	14.49	119.72	0.2343	813.	548.
97	21 2	407	386.	204.	8647.	11362.	14 36	119.72	0 2264	812.	548
98	19.1	459.	387.	198.	8752.	10316.	13.69	111.59	0.2615	820.	547.
99	18 3	459	401	207	8396.	11362.	14.66	119 72	0 2551	842	548
100	21.3	419.	403.	228	8900.	12180	15.35	122.37	0.2232	834.	568
101	18.5	415.	366.	182.	7685.	9613	14.08	111 67	0.2521	788.	512.
102	18.1	470.	406.	206.	8501.	11248.	14.35	116.98	0.2582	850.	559.
103	20.6	429.	394.	215.	8858.	11248.	15.10	116.98	0.2359	824.	559.
104	10.7	475	469.	116.	5086.	6912.	6.72	70.72	0.2571	976.	671.
105	8 2	533.	503.	118.	4397.	6147.	6 91	62.55	0 2874	1044.	703
106	10.0	494.	464.	115.	4962.	6817.	7 02	71.83	0.2747	975.	650
107	10 9	488.	479	118	5317.	7262	6 49	72 33	0.2579	987	683.
108	10.4	459.	490.	124.	4795.	7194.	6.83	70 68	0.2399	1005.	697.
109	9.4	469.	477.	108.	4397.	6262.	6 24	65.29	0.2582	997.	677.
110	14.0	428.	442.	136.	5966.	7864.	8.45	79 96	0.2304	918.	648.
111	13.0	443.	439	130	5737.	7537.	8.24	78.90	0.2448	919	633
112	11 2	498.	455.	127	5569.	7537	7 91	78 90	0.2752	953	633
113	10 5	473.	463	125.	4962.	6517.	7.71	68.01	0.2610	970	667.
114	15.8	473.	416.	125.	7495.	9322.	7 69	97 95	0.2626	873.	587.
115	18.9	459.	388.	154.	8669.	10316.	10.64	111.59	0.2611	822.	547.
116	20.6	446.	373.	143.	9192.	11820.	9.86	130.67	0.2592	794.	509.

STATION NUMBER 3

RUN	DT	H	HNU	HBK	Q/A LOC	CONDENS.	VAP VEL	X	Y	HAT1	HAT2
75	22 3	402	310	103	8943	11002	6.25	208 03	0 2441	666	416
76	23 1	346	313	126	8002	10773	8 35	199.13	0 2064	671	431.
77	22 1	398	335	134	8805	11477	8 15	198 99	0.2238	707	457
78	24.7	363.	333.	139.	8945.	12523.	8.56	212.20	0.1998	698.	457.
79	19.5	382.	332.	119.	7429.	9269.	7.45	168.12	0.2235	708	464.
80	20 0	384.	322.	120.	7689.	9498.	8.11	177 02	0.2307	691.	445.
81	19.5	410	333.	118.	7991	9780	5 91	176 96	0.2398	709	457
82	20 1	365	343	149	7328.	10202.	9 99	176 88	0.2052	723	476
83	20 2	380.	333	118.	7691	9433	7 42	168 98	0 2203	707	468
84	19.7	398.	331.	116.	7851.	9802.	7.27	177.85	0.2330	706.	455.
85	17.9	390.	323.	97	6988.	8337	6.17	159.36	0.2395	697.	450.
86	18.0	407.	347.	116.	7331.	9041	7.01	159 22	0.2322	736.	485.
87	18 3	397	349	116	7267	9482	6 75	165 39	0 2242	737	484
88	18 7	414	343	145	7751	9597	9 12	169 84	0 2372	726	473
89	19 9	382	357	120	7628.	9858	6 76	163 53	0 2068	744	509
90	20.7	372.	359	122.	7707	9744.	7.01	159 08	0.1983	743.	521.
91	19.9	373	349.	118.	7425.	9322.	7.00	159.16	0.2072	732.	500.
92	21 8	355.	342	115	7747	9531.	6 66	161.81	0 1958	718.	500.
93	21 8	352	319	146	7666	9384	8 28	172 57	0 2085	683	454
94	23 0	348	332	149	7991	10202	9 22	176.88	0.1956	700	476
95	23 2	364	333	179	8451	10643	11 58	183 05	0 2033	702	474
96	37.9	126.	297.	204.	4765.	11362.	13.85	194.54	0.0699	626.	466.
97	37.1	122	299.	199.	4537.	11362.	13.72	194.54	0.0680	629.	466.
98	36.9	126.	292.	194.	4665.	10316.	13.11	181.33	0.0720	620.	466.
99	35 8	123	301.	202	4425.	11362.	14.02	194.54	0 0687	634	466
100	37.1	129.	312	223	4772	12180	14 65	198.85	0.0687	647	484
101	21.7	378	312	178	8181.	9613.	13 55	181 47	0 2293	672	436
102	23.1	373.	339.	202.	8618.	11248.	13.70	190.09	0.2048	710.	475.
103	22.6	410.	341.	210.	9280.	11248	14.45	190.09	0.2255	714.	475.
104	13.0	417.	396.	112.	5442.	6912.	6.32	114.92	0.2259	824.	571.
105	11 4	422.	412.	115	4797	6147	6 56	101.65	0.2274	855	598
106	11 5	476.	397.	112.	5502.	6817.	6 63	116 72	0 2650	834	553
107	14.7	390.	394.	115.	5742.	7262.	6.07	117 53	0.2065	812.	581
108	12.9	408.	411.	121.	5278.	7194.	6.42	114.86	0.2130	844.	593.
109	11.6	421.	400.	105.	4896	6262.	5.89	106.10	0.2319	838.	576.
110	16.0	392.	379.	133.	6260,	7864.	8.00	129.93	0.2111	787.	551.
111	16 4	364	367.	126.	5959.	7537.	7 81	128.21	0.2014	769	539
112	15.6	376.	371.	124.	5858.	7537	7 49	128 21	0.2079	778	539.
113	13 3	398.	387.	122	5295.	6517	7 34	110 52	0 2194	810.	568
114	20.0	376.	348.	120.	7521.	9322.	7.16	159.16	0.2084	731.	500.
115	25.3	353.	320.	150.	8938.	10316.	10.05	181.33	0.2009	678.	466.
116	25.7	358.	313.	138.	9214	11820.	9.20	212.34	0.2080	666.	433.

STATION NUMBER 4

RUN	DT	H	HNU	HBK	Q/A LOC	CONDENS.	VAP VEL	X	Y	HAT1	HAT2
75	23 2	403	283	98	9365	11002	5 64	288 04	0 2453	608	373
76	22 4	382.	291	121	8546	10773	7 75	275 72	0 2275	623	386.
77	22 9	395	306	129	9052	11477	7 50	275 52	0 2222	646	410
78	23.7	397.	310.	133.	9407.	12523.	7.84	293 81	0.2189	650.	410.
79	18 4	421.	310.	115.	7737.	9269.	6 94	232.78	0.2465	662.	416
80	18.7	425.	302	116.	7967.	9498.	7.59	245 11	0 2550	647.	399.
81	21 5	361	299	114	7761	9780	5 37	245 03	0 2108	638	410
82	19 1	399.	320	145	7634	10202	9 41	244 91	0 2246	675	427
83	20.5	378	305.	114.	7762	9433	6 89	233.98	0 2189	650	420
84	20.4	381.	302.	112.	7785.	9802.	6 72	246.26	0.2232	645	408.
85	18.4	390.	296.	94.	7190.	8337.	5 72	220.65	0.2397	638.	403.
86	20.2	358.	311	112	7237.	9041	6 50	220 46	0 2043	659.	436.
87	20 4	358	313	111	7296	9482	6 21	229 01	0 2025	662	434
88	20 1	383	311	140	7677	9597	8 58	235.17	0 2193	659	424
89	20 6	376	327	115	7739	9858	6 19	226 42	0 2034	680	456
90	21.6	360.	328.	117.	7783.	9744.	6.45	220.26	0.1920	678.	467.
91	20 0	384	321.	114.	7655.	9322	6.47	220.38	0 2128	674.	448.
92	20 7	384.	320	110.	7974.	9531.	6.12	224 04	0.2121	670.	448.
93	21 7	368	294	142	7997	9384	7 75	238 94	0 2184	630	407
94	20 9	406	313	145	8499	10202	8 64	244 91	0.2282	660	427
95	23 3	365	307	175	8522	10643.	10 97	253.46	0 2038	646.	425
96	25.2	354.	303.	199.	8916.	11362.	13.20	269.36	0.1970	636.	418.
97	24.8	357.	304.	194.	8838.	11362.	13.07	269.36	0.1986	639.	418.
98	26.4	328.	292.	189.	8669.	10316.	12.53	251.07	0.1869	619.	418.
99	24.9	345	304	198.	8586	11362	13 37	269 36	0.1921	638	418
100	26 5	339	312	218	8987	12180	13 95	275 33	0 1805	646	434.
101	22 0	382	287	174	8414	9613	13 02	251.27	0 2322	617	391
102	23.1	382.	313.	197.	8800.	11248.	13.06	263.20	0.2098	655.	427.
103	25.8	346.	304.	206.	8925.	11248.	13.81	263.20	0.1904	638.	427.
104	14 2	387.	358.	109.	5485.	6912.	5.92	159.11	0.2097	744.	512.
105	12.9	356	368.	112	4576	6147	6 21	140 75	0 1917	764	536.
106	15.6	351.	340	108	5465.	6817.	6 24	161 62	0 1953	715	496
107	15.6	387.	358.	111.	6032.	7262.	5 65	162.73	0 2045	738.	521
108	14.6	370.	368.	117.	5378.	7194.	6.00	159.04	0.1932	756.	532.
109	13.2	378	358.	102.	4977.	6262.	5 53	146.91	0.2084	749.	517.
110	17.0	376.	344.	129.	6410.	7864.	7 55	179.91	0.2028	714.	494.
111	15.7	396	342	123	6224	7537.	7 38	177 52	0 2191	716	483
112	16.7	358.	337	120.	5968.	7537.	7.06	177.52	0 1977	705	483.
113	14 3	370	351	119	5295	6517	6 97	153 03	0 2043	734	509
114	20.7	384.	318.	116.	7952	9322.	6.63	220 38	0.2130	668.	448.
115	25.4	348.	295.	145.	8840.	10316.	9 47	251.07	0 1983	625.	418.
116	25.9	370.	288.	133.	9601	11820.	8 53	294.01	0.2151	613.	388.

STATION NUMBER 5

RUN	DT	H	HNU	HBK	Q/A LOC	CONDENS.	VAP VEL	X	Y	HAT1	HAT2
75	27 6	372	255	92.	10267	11002	5 04	368 05	O 2259	549	344
76	24 3	397	268	116.	9641	10773	7 15	352.31	O 2365	575	356
77	26 2	375	279	123.	9843.	11477	6 85	352 06	O 2109	588	378
78	25.8	393	285.	127	10166.	12523.	7.13	375.43	0.2168	598.	378.
79	21.5	386	281.	110.	8319.	9269.	6.42	297.44	O 2263	599	384
80	23.1	366.	270.	111.	8440.	9498.	7.06	313.19	0.2197	579.	368.
81	24 4	341	273.	109	8341	9780	4 82	313 09	O 1996	582	378
82	24 0	341	285	140	8179	10202	8 84	312 94	O 1921	601	393
83	23 8	356	277	109	8460	9433	6 36	298 97	O 2059	590	387
84	23.2	366	276.	107	8500.	9802.	6.18	314.67	0 2144	588.	376.
85	21.8	363	267.	90.	7891.	8337.	5.26	281.95	O 2226	577.	372.
86	22.9	347	284.	107.	7955.	9041.	5.99	281 70	0.1977	601.	401
87	23 5	337	285	106	7913	9482	5 68	292 62	0.1904	602	400
88	24 4	333	278	136	8137	9597	8 04	300 49	O 1908	591	391
89	24 7	335	294	110	8258	9858	5 63	289 32	O 1810	613	420
90	26.7	301.	293	112.	8032.	9744.	5.89	281 45	0.1605	607.	431.
91	24.4	339	287	109.	8278.	9322.	5 94	281 60	O 1879	604	413
92	25 1	340	287	105.	8520	9531.	5.57	286.27	0.1876	602.	413.
93	25 0	355	267	138	8887	9384	7 23	305 32	O 2105	573	375
94	26 6	338	278	140	8988	10202	8 06	312 94	O 1899	586	393
95	26.3	352	280	170	9272	10643	10 37	323 86	O 1967	590	392
96	29.4	322.	274.	195.	9477.	11362.	12.56	344.18	0.1790	576.	385.
97	28 9	329	275.	190.	9494.	11362	12 43	344.18	0.1827	579.	385.
98	28.9	330	269	185	9536.	10316	11.95	320 81	0.1878	570.	385.
99	28 0	336	277	193	9416	11362	12 73	344.18	O 1867	583	385
100	31 0	302	282	213	9356	12180	13 25	351 81	0.1610	585	400
101	28 5	315	253	170	8990	9613	12 49	321 06	O 1912	545	360
102	28.5	331.	279.	193.	9456	11248.	12.42	336.31	0.1821	585.	393
103	30.0	318.	276.	201.	9557.	11248	13.17	336.31	0.1750	578.	393.
104	17 3	355.	320	106	6127.	6912.	5.53	203 31	0.1921	667.	472
105	15 0	341	333	109	5133	6147	5 86	179 84	O 1841	692	494
106	17 9	353	309	105	6310	6817	5 86	206 51	O 1961	650	457
107	19 0	364.	321.	107	6917.	7262	5 23	207.94	O 1923	661	480
108	19.1	313.	324.	113.	5985.	7194	5.59	203.21	0.1637	665	490.
109	16.1	354	320.	99.	5700.	6262.	5.17	187.71	0.1950	671.	476.
110	21.1	339.	307.	125.	7141.	7864.	7.10	229.88	0.1826	638.	456.
111	20 6	331	300.	119	6838	7537	6 95	226.83	O 1831	630	445
112	20.1	329.	302	117	6614.	7537	6.63	226 83	0.1819	634	445
113	18 6	308	309	115	5723.	6517.	6 60	195.54	O 1696	647	469.
114	25.1	352.	285.	111.	8848.	9322.	6.10	281.60	0.1952	600.	413
115	28.2	354.	271.	141.	9962.	10316.	8 89	320.81	0.2015	573.	385.
116	30.6	342.	260.	128	10489.	11820.	7 87	375.68	0 1988	554.	358.

APPENDIX F

R-113 CONDENSATION

Sample Calculations

Sample Run #128

R-113 Properties

	Vapor	Liquid
k Btu/hr•ft•°F		0.038
ρ lb/ft^3		97.81
λ Btu/lb	63.13	
μ lb/hr•ft		1.646
Cp Btu/lb•°F		0.218

SS 304 thermal conductivity = 9.0 Btu/hr•ft•°F

Station #3

Location	Displacement (inch)	Temperature (°F)
Vapor	-	114.2
Front	0.0240	90.2
Middle	0.0335	84.1
Back	-0.0113	77.3

Best fit straight line for the temperature gradient through the SS 304 plate:

$y = A_0 + A_1 x$

$y \equiv$ temperature, °F

$x \equiv$ distance from front surface, inch

x	y
0.25 - 0.0240	90.8
0.5 - 0.0335	84.1
0.75 + 0.0113	77.3

$\Sigma\, xy = 118.6$ $\qquad \Sigma\, y = 252.2$

$\Sigma\, x = 1.4538$ $\qquad \Sigma\, x^2 = 0.8483$

$\Sigma i = 3$

$$A_1 = \frac{\Sigma\, xy * \Sigma\, i - \Sigma\, y * \Sigma\, x}{\Sigma\, i * \Sigma\, x^2 - \Sigma\, x * \Sigma\, x} = -25.14$$

$$A_0 = \frac{\Sigma\, y - A_1\ \Sigma\, x}{\Sigma\, i} = 96.25$$

At the front surface, x = 0

$T_s = 94.25 - 25.14 * x$

$= 96.25°F$

ΔT across the condensate

$= T_v - T_s$

$= 114.2 - 96.25$

$= 18.0°F$

Heat flux through the SS 304 plate

$$\frac{Q}{A} = K \frac{\Delta T}{\Delta x}$$

$$= \frac{9.0 * [96.24 - (96.25 - 25.14 * 1)]}{1/12}$$

$$= 2715 \text{ Btu/hr}\cdot\text{ft}^2$$

Condensing heat transfer coefficient

$$h = \frac{Q/A}{\Delta T} = \frac{2715}{18.0}$$

$$= 151 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

Prediction based on Nusselt's equation

$$h = \left[\frac{k_l^3\ \rho_l^2\ g\lambda}{4\ \mu_l\ (T_v - T_s)\ x}\right]^{1/4} * \left[1 + 0.68\ \frac{Cp_l\ (T_v - T_s)}{\lambda}\right]^{1/4}$$

$$= \left[\frac{0.038^3 * 97.81^2 * 32 * 3600^2 * 63.13}{4 * 1.646 * 18.0 * 13/12}\right]^{1/4}$$

$$* \left[1 + 0.68 * \frac{0.218 * 18.0}{63.13}\right]^{1/4}$$

$$= 103\ \text{Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

$$\%\ \text{Error} = \frac{151 - 103}{103} * 100$$

$$= 46.6\%$$

Condensate Reynolds number and condensation number

Condensate rate = 97.5 ml/min

$$= 97.5 * \frac{1}{1000} * \frac{1}{28.32} * 60 * 97.81$$

$$\frac{\text{ml}}{\text{min}} * \frac{\text{lit}}{\text{ml}} * \frac{\text{ft}^3}{\text{lit}} * \frac{\text{min}}{\text{hr}} * \frac{\text{lb}}{\text{ft}^3}$$

$$= 20.2\ \text{lb/hr}$$

Condensate loading

$$\Gamma = \frac{\text{condensate rate}}{\text{perimeter}}$$

$$= \frac{20.2}{2/12} = 121.23\ \text{lb/hr}\cdot\text{ft}$$

Local condensate Reynolds number

$$= \frac{4\Gamma}{\mu_l}$$

$$= \frac{4 * 121.23 * 13/26}{1.646}$$

$$= 147.3$$

Local condensation number

$$= h \left[\frac{k_l^3 \rho_l^2 g}{\mu_l^2}\right]^{-1/3}$$

$$= 0.3499$$

SOURCE CODE

```
$JOB
C23456789
      DIMENSION T(70,20),NRUN(70),DLOC(5),NV(5),NF(5),NM(5),NB(5)
      DIMENSION XT(3,5),C(3),D(3)
      DIMENSION XP(25),YP(25),XPP(125),YPP(125),W1(25),W2(25)
      DATA KW,KXYP/6,0/
      DATA NV/1,17,18,19,20/
      DATA NF/16,5,7,14,13/
      DATA NM/2,4,8,10,11/
      DATA NB/3,6,9,12,15/
      DATA DLOC/3.,8.0,13.0,18.0,23.0/
      DATA XT/0.016,0.0151,0.0123,0.0144,0.0144,-0.0013,0.024,0.0335,-0.
     #0113,0.0144,0.0229,0.0019,0.0323,0.0256,0.0008/
C     DATA XT/15*0.0/
      DATA LF/11/
      MPT=0
10    K=MPT+1
      READ(5,*,END= 99)NRUN(K)
      MPT=MPT+1
      READ(5,*) (T(MPT,I),I=2,10)
      READ(5,*) (T(MPT,I),I=11,20)
      READ(5,*)W1(MPT),W2(MPT)
      T(MPT,1)=(T(MPT,17)+T(MPT,18)+T(MPT,19)+T(MPT,20))/4.0
      GO TO 10
99    CONTINUE
      HN=397.83
      C(1)=0.25
      C(2)=0.5
      C(3)=0.75
      DO 60 NST=1,5
      J1=NV(NST)
      J2=NF(NST)
      J3=NM(NST)
      J4=NB(NST)
      WRITE(6,21)
 21   FORMAT(1H1,//////,'   ')
      WRITE(6,20)NST,(XT(J,NST),J=1,3)
20    FORMAT(18X,' STATION NUMBER',I3,/,13X,3F10.5,//,8X,
     #'RUN',2X,'  TV   ','   TF   ','   TM   ','   TB   ',2X,'DT',5X,
     #'H',5X,'HNU',5X,'% ERR',4X,'Q/A',7X,'X',7X,'Y',5X,'ML/M',/)
      DO 40 I=1,MPT
      SYXW=0.0
      SY=0.0
      SI=3
      SXW=0.0
      SXWXW=0.0
      D(1)=T(I,J2)
      D(2)=T(I,J3)
      D(3)=T(I,J4)
      DO 30 J=1,3
      SYXW=SYXW+D(J)*(C(J)-XT(J,NST))
      SY=SY+D(J)
      SXW=SXW+C(J)-XT(J,NST)
30    SXWXW=SXWXW+(C(J)-XT(J,NST))**2
      A1=(SYXW*SI-SY*SXW)/(SI*SXWXW-SXW*SXW)
      A0=(SY-A1*SXW)/SI
      DT=T(I,J1)-A0
      Q=-A1*108.0
      H=-A1*108.0/DT
      HNU=HN/(DLOC(NST)*DT)**0.25
      HNU=HNU*(1.0+0.68*0.218*DT/63.13)**0.25
      PCER=(H-HNU)/HNU*100.0
      YP(I)=H/431.52
      XP(I)=W1(I)*DLOC(NST)*0.1162
      WRITE(LF,210)XP(I),YP(I)
 210  FORMAT(1X,F10.5,2X,F8.4)
      WRITE(6,50)NRUN(I),T(I,J1),T(I,J2),T(I,J3),T(I,J4),DT,H,HNU,PCER,Q
     @,XP(I),YP(I),W1(I)
40    CONTINUE
 50   FORMAT(8X,I3,4(1X,F5.1),1X,F5.1,2(1X,F6.0),2X,F7.1,2X,F7.0,2X,F6.2
     #,2X,F6.4,2X,F6.2)
      WRITE(LF,220)
```

```
 220   FORMAT(1X,'   ')
60     CONTINUE
       WRITE(6,21)
       STOP
       END
$ENTRY
117
85.6,78.5,83.5,90.5,76.5,88.8,81.6,74.0,80.7
77.1,73.1,85.1,86.5,70.1,92.4,114.5,114.1,114.2,114.2
110.0,117.5
118
85.3,78.0,83.2,90.3,76.0,88.4,81.1,73.5,80.4
76.7,72.5,84.7,86.1,69.5,91.8,114.3,114.1,114.3,114.5
108.0,137.5
119
85.5,78.2,83.5,90.7,76.4,88.5,81.3,73.7,80.7
76.7,72.9,84.6,86.5,69.7,92.2,114.7,114.4,114.5,114.7
107.5,57.5
120
85.9,78.2,83.7,91.0,76.2,88.9,81.4,73.5,80.7
76.9,72.7,85.1,86.7,69.5,92.5,115.3,115.2,115.5,115.8
115.0,222.5
121
86.9,80.1,84.8,91.6,77.8,89.3,82.3,75.2,81.3
77.4,73.9,85.1,87.1,70.9,93.5,114.5,114.3,114.5,114.5
105.0,112.5
122
87.2,80.4,85.1,91.9,78.2,89.8,82.7,75.6,81.5
77.7,74.0,85.6,87.3,70.7,93.6,114.7,114.5,114.7,114.9
115.0,170.0
123
85.7,78.3,83.5,90.9,76.1,88.7,81.2,73.5,80.8
76.9,72.8,85.3,87.1,69.8,93.5,115.8,115.4,115.7,115.8
117.5,227.5
124
88.0,81.4,85.7,92.5,78.9,90.2,83.1,76.0,81.7
77.7,74.0,85.7,87.5,70.7,94.5,114.9,114.5,114.8,115.0
107.5,212.5
125
89.1,82.1,86.5,93.5,79.4,91.1,83.8,76.4,82.6
78.3,74.5,86.5,88.5,70.9,95.6,116.1,115.9,116.3,116.5
115.0,335.0
126
89.8,83.3,87.3,94.0,80.7,91.8,84.9,77.9,83.5
79.4,76.0,87.4,89.4,72.6,96.5,115.9,115.5,115.8,115.9
105.0,225.0
127
89.1,82.9,86.9,93.4,80.5,91.1,84.4,77.5,82.9
78.8,75.6,86.3,88.4,72.0,95.3,114.8,114.5,114.7,114.8
100.0,122.5
128
89.0,82.8,86.9,93.3,80.4,90.8,84.1,77.3,82.2
78.1,75.0,85.4,87.6,71.4,94.7,114.4,114.2,114.4,114.4
97.5,72.5
129
99.0,94.7,97.5,101.8,93.3,100.6,96.2,91.6,95.3
93.1,90.7,98.3,99.1,88.9,103.1,115.1,114.9,115.1,115.1
67.5,187.5
130
98.8,94.6,97.5,101.6,93.3,100.3,96.0,91.4,95.1
92.9,90.6,97.8,98.7,88.6,102.5,114.3,114.1,114.2,114.4
66.7,155.0
131
98.8,94.7,97.4,101.4,93.2,100.2,95.8,91.2,94.9
92.6,90.2,97.5,98.3,88.2,102.1,114.0,113.8,114.0,114.2
70.0,152.5
132
89.1,82.9,86.8,93.3,80.4,91.1,84.3,77.5,82.8
78.7,75.5,86.5,88.6,72.1,95.6,115.1,114.7,114.8,115.0
107.5,175.0
$IBSYS
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RESULTS

Nomenclature for Data Printout

TV	vapor temperature, °F
TF	front thermocouple, °F
TM	middle thermocouople, °F
TB	back thermocouple, °F
DT	ΔT_f, °F
H	condensing coefficient, Btu/hr-ft^2-°F
HNU	H calculated by Nusselt equation
%ERR	(H - HNU)/HNU * 100
Q/A	local heat flux, Btu/hr-ft^2
X	local condensate Reynolds number
Y	local condensation number
ML/M	condensate volumetric flow rate, ml/min

STATION NUMBER 1

0.01600 0.01510 0 01230

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
117	114.2	92.4	85.6	78.5	15.4	194	154.	26 0	2980.	38 35	0.4499	110.00
118	114.3	91.8	85.3	78.0	16.0	185.	153.	21.4	2959.	37.65	0.4296	108 00
119	114.6	92.2	85.5	78 2	15.8	190.	153.	24.3	3002.	37.47	0.4409	107.50
120	115 4	92 5	85 9	78 2	16 1	190	152	24 8	3066	40 09	0 4405	115 00
121	114 4	93.5	86 9	80 1	14 7	195	156	25 5	2873	36 60	0 4529	105 00
122	114 7	93 6	87 2	80 4	14 9	190	155	22 3	2830	40 09	0 4399	115 00
123	115.7	93.5	85.7	78.3	15.2	215.	154	38.9	3259.	40.96	0.4972	117.50
124	114.8	94.5	88.0	81 4	14.2	198.	157.	25.9	2809.	37.47	0 4582	107.50
125	116.2	95.6	89.1	82.1	14.3	203.	157.	29.5	2895.	40.09	0.4706	115 00
126	115 8	96 5	89 8	83 3	13 2	215	160	34 3	2830	36 60	0 4974	105 00
127	114 7	95 3	89 1	82 9	13 6	195.	159	22 9	2659	34 86	0 4514	100 00
128	114 3	94 7	89 0	82 8	14 0	182	157	15 4	2552	33 99	0 4210	97 50
129	115.0	103.1	99.0	94 7	8.0	225.	180	24.4	1801.	23 53	0 5204	67 50
130	114.2	102.5	98.8	94.6	8.0	212.	181	17 2	1694.	23.25	0.4906	66.70
131	114.0	102.1	98 8	94.7	8.3	190	179	6.5	1587	24 40	0.4412	70 00
132	114 9	95 6	89 1	82 9	13 5	202	159	27 2	2723	37 47	0 4688	107 50

STATION NUMBER 2

0.01440 0.01440 -0.00130

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
117	114.5	90.5	83.5	76.5	17.7	166	117.	42 3	2931.	102.26	0.3842	110.00
118	114.3	90.3	83.2	76.0	17.5	171	117.	46.3	2994.	100.40	0.3959	108.00
119	114 7	90.7	83.5	76.4	17.6	170.	117.	46.0	2994.	99 93	0.3950	107 50
120	115 3	91.0	83 7	76 2	17 6	176	117	51 0	3099	106 90	0 4084	115 00
121	114 5	91 6	84 8	77 8	16 6	174.	118	46 9	2890	97 61	0 4026	105 00
122	114.7	91 9	85 1	78 2	16 6	173	118	46 1	2868	106 90	0 4005	115 00
123	115.8	90.9	83.5	76.1	18.2	170.	116.	47.0	3099.	109.23	0.3941	117.50
124	114.9	92 5	85 7	78 9	16.3	175.	119.	47 3	2847	99.93	0.4058	107.50
125	116.1	93.5	86.5	79.4	16.2	182	119	53 0	2952.	106.90	0.4219	115.00
126	115 9	94 0	87 3	80 7	15 9	175	120	46 4	2784	97 61	0 4055	105 00
127	114 8	93 4	86 9	80 5	15 6	173	120	44 2	2700	92 96	0 4013	100 00
128	114 4	93 3	86 9	80 4	15 3	177	121	46 6	2701	90 64	0 4102	97 50
129	115.1	101.8	97.5	93.3	9 5	188	136.	38.5	1779	62.75	0.4349	67.50
130	114.3	101.6	97 5	93.3	8.9	194.	138.	41.4	1738.	62.00	0.4507	66.70
131	114.0	101.4	97 4	93.2	8 9	194	138.	40 6	1717.	65.07	0.4490	70 00
132	115 1	93 3	86 8	80 4	16 0	169	119.	41 4	2701	99 93	0 3913	107 50

STATION NUMBER 3

0.02400 0.03350 -0.01130

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
117	114.1	88.8	81.6	74.0	19.3	155.	101.	52.9	2978.	166.17	0.3582	110.00
118	114.1	88 4	81.1	73 5	19.6	153.	101.	51 6	2998.	163.14	0.3536	108.00
119	114.4	88.5	81.3	73.7	19 9	150	100	49 3	2978.	162.39	0.3474	107 50
120	115 2	88 9	81 4	73 5	20 0	155	100.	54 5	3099	173 72	0 3586	115 00
121	114 3	89 3	82 3	75 2	19 3	147	101	45 3	2836	158 61	0 3403	105 00
122	114 5	89 8	82 7	75 6	19 0	150	101	48 2	2855	173 72	0 3484	115 00
123	115 4	88.7	81 2	73.5	20.5	149	100	49 4	3057.	177.50	0.3448	117.50
124	114.5	90 2	83.1	76 0	18.6	154.	102.	50 6	2855.	162.39	0.3559	107.50
125	115.9	91.1	83.8	76.4	18 9	157.	102.	54 2	2956	173.72	0.3631	115.00
126	115 5	91 8	84 9	77 9	18 1	155	103	50 5	2795	158 61	0 3581	105 00
127	114 5	91 1	84 4	77 5	17 9	153	103	48 6	2736.	151 06	0 3543	100 00
128	114 2	90 8	84 1	77 3	18 0	151	103	47 1	2715	147 28	0 3505	97 50
129	114.9	100.6	96 2	91 6	10 6	170.	117.	45 8	1811.	101.97	0.3943	67.50
130	114.1	100 3	96.0	91.4	10.2	176.	118.	49 3	1791.	100.76	0 4085	66.70
131	113 8	100.2	95.8	91.2	9.9	182.	119	53.5	1811.	105 74	0 4221	70 00
132	114 7	91 1	84 3	77.5	18 1	151	103	47 0	2734	162 39	0 3495	107 50

STATION NUMBER 4

0.01440 0 02290 0 00190

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
117	114.2	86.5	80.7	73.1	21.3	132.	91.	45.6	2828.	230 08	0.3070	110.00
118	114.3	86.1	80.4	72.5	21.7	132.	91.	46.1	2872.	225.89	0.3069	108.00
119	114.5	86.5	80.7	72.9	21.5	133.	91.	46.9	2871.	224.85	0.3091	107.50
120	115 5	86 7	80 7	72 7	22 1	133	90	48 0	2955	240 53	0 3093	115 00
121	114 5	87.1	81 3	73 9	21 2	132	91	44 3	2785	219 62	0 3048	105 00
122	114 7	87 3	81 5	74 0	21 1	133	91	45 7	2806	240 53	0 3080	115 00
123	115 7	87.1	80.8	72.8	21 9	138.	90	52.6	3017.	245.76	0.3198	117.50
124	114.8	87 5	81.7	74 0	20 9	136	91.	49.2	2849.	224.85	0.3162	107 50
125	116.3	88.5	82 6	74.5	21.1	140.	91	53 5	2956.	240 53	0 3245	115.00
126	115 8	89 4	83 5	76 0	20 1	141	92	52 5	2827	219 62	0 3262	105 00
127	114 7	88 4	82 9	75 6	20 2	134	92	45 0	2702.	209 16	0 3096	100 00
128	114 4	87 6	82 2	75 0	20 8	128	92	39 7	2660	203 93	0 2962	97 50
129	115 1	99.1	95.3	90.7	12.1	147.	104	40 5	1771.	141.18	0.3398	67 50
130	114.2	98.7	95.1	90 6	11 7	146	105.	38 9	1709.	139.51	0 3385	66.70
131	114 0	98.3	94 9	90.2	11 8	145	105.	37 9	1710	146 41	0.3352	70 00
132	114 8	88 6	82 8	75 5	20 0	138	92	49 3	2764	224.85	0 3196	107 50

STATION NUMBER 5

0 03230 0.02560 0 00080

RUN	TV	TF	TM	TB	DT	H	HNU	% ERR	Q/A	X	Y	ML/M
117	114.2	85.1	77 1	70.1	23.2	131.	84.	56.3	3044.	293.99	0.3038	110.00
118	114.5	84.7	76.7	69 5	23.8	130.	83	55 5	3086.	288 64	0.3003	108 00
119	114.7	84.6	76.7	69 7	24 2	125.	83.	50 3	3024.	287.30	0.2891	107.50
120	115 8	85 1	76 9	69 5	24 5	129	83	55 9	3167	307 35	0 2990	115 00
121	114 5	85 1	77 4	70 9	23 9	121	83	44 8	2882	280 62	0 2796	105 00
122	114 9	85 6	77 7	70 7	23 4	129.	84	54 2	3024	307 35	0.2989	115.00
123	115.8	85.3	76 9	69.8	24 5	129	83	55 2	3145	314.03	0.2978	117 50
124	115.0	85.7	77 7	70 7	23.4	130.	84	55.3	3044.	287.30	0.3012	107.50
125	116.5	86.5	78 3	70 9	23 8	133	83	59 4	3167	307.35	0.3078	115 00
126	115 9	87 4	79 4	72 6	22 7	132	84	56 7	3003	280 62	0 3061	105 00
127	114 8	86 3	78 8	72 0	22 9	127	84	50 9	2903	267 26	0 2944	100 00
128	114 4	85 4	78 1	71 4	23 5	121	84	44.8	2842	260 58	0 2808	97 50
129	115.1	98.3	93.1	88.9	13 2	145	96.	50.6	1907.	180.40	0.3352	67.50
130	114.4	97.8	92.9	88 6	13.0	144.	96.	49 1	1867.	178.26	0.3330	66 70
131	114 2	97.5	92.6	88.2	13 0	145	96.	50.3	1888.	187.08	0.3356	70 00
132	115 0	86 5	78 7	72 1	22 9	128	84	51 7	2922	287 30	0 2957	107 50

APPENDIX G

R-113-WATER MIXTURE CONDENSATION

Sample Calculations

Sample Run #137

R-113 and Water Properties

	Water		R-113	
	Vapor	Liquid	Vapor	Liquid
k Btu/hr•ft•°F		0.37		0.038
ρ lb/ft^3	1/245	61.8	0.4604	97.81
λ Btu/lb	1030		63.18	
μ lb/hr•ft		1.525		1.646
Cp Btu/lb•°F		1.0		0.212

SS 304 thermal conductivity = 9.0 Btu/hr•ft•°F

Station #5

Location	Displacement (inch)	Temperature (°F)
Vapor	-	112.8
Front	0.0323	85.0
Middle	0.0256	77.1
Back	0.0008	71.0

Test cell condensation rate

R-113: 95 ml/min

Water: 0.1 ml/min

Auxiliary condenser condensation rate

R-113: 320 ml/min

Water: 3.4 ml/min

Mixture properties evaluation

Condensation rates

R-113: 95 ml/min

$$= 95 * \frac{1}{1000} * \frac{1}{28.32} * 60 * 97.81$$

$$\frac{ml}{min} * \frac{lit}{ml} * \frac{ft^3}{lit} * \frac{min}{hr} * \frac{lb}{ft^3}$$

= 19.69 lb/hr

Water: 0.1 ml/min

$$= 0.1 * \frac{1}{1000} * \frac{1}{28.32} * 60 * 61.8$$

$$\frac{ml}{min} * \frac{lit}{ml} * \frac{ft^3}{lit} * \frac{min}{hr} * \frac{lb}{ft^3}$$

= 0.0131 lb/hr

Mixture thermal conductivity K_l

$$k_l = \frac{w_w k_w + w_o k_o}{w_w + w_o}$$

$$= \frac{0.37 * 0.0131 + 0.038 * 19.69}{0.0131 + 19.69}$$

$$= 0.03822 \text{ Btu/hr·ft·}^0\text{F}$$

Mixture vapor density

$$\rho_v = \frac{w_w + w_o}{\frac{w_w}{\rho_{v_w}} + \frac{w_o}{\rho_{v_o}}}$$

$$= \frac{0.0131 + 19.69}{0.0131 * 245 + \frac{19.69}{0.4604}}$$

$$0.4285 \text{ lb/ft}^3$$

Mixture liquid density

$$\rho_l = \frac{\rho_{l_w} v_w + \rho_{l_o} v_o}{v_w + v_o}$$

$$= \frac{61.8 * 0.1 + 97.81 * 95}{0.1 + 95}$$

$$= 97.77 \text{ lb/ft}^3$$

Mixture liquid viscosity

$$\mu_l = \frac{w_w + w_o}{\frac{w_w}{\mu_{lw}} + \frac{w_o}{\mu_{lo}}}$$

$$= \frac{0.0131 + 19.69}{\frac{0.0131}{1.525} + \frac{19.69}{1.646}}$$

$$= 1.6459 \text{ lb/hr·ft}$$

Mixture liquid specific heat

$$C_{p_l} = \frac{w_w \, Cp_{lw} + w_o \, Cp_{lo}}{w_w + w_o}$$

$$= \frac{0.0131 * 1 + 19.69 * 0.212}{0.0131 + 19.69}$$

$$= 0.2125 \text{ Btu/lb}\cdot{}^{0}\text{F}$$

Best fit straight line for the temperature gradient through the SS 304 plate:

$y = A_0 + A_1 x$

$y \equiv$ temperature, °F

$x \equiv$ distance from front surface, inch

x	y
0.25 - 0.0323	85.0
0.5 - 0.0256	77.1
0.75 + 0.0008	71.0

$\Sigma\, xy = 1087.27$ $\Sigma\, y = 233.1$

$\Sigma\, x = 1.4413$ $\Sigma\, x^2 = 0.8337$

$\Sigma i = 3$

$$A_1 = \frac{\Sigma\, xy * \Sigma\, i - \Sigma\, y * \Sigma\, x}{\Sigma\, i * \Sigma\, x^2 - \Sigma\, x * \Sigma\, x} = -26.292$$

$$A_0 = \frac{\Sigma\, y - A_1\, \Sigma\, x}{\Sigma\, i} = 90.33$$

At the front surface, x = 0

T_s = 90.33 - 26.292 * x

= 90.33°F

ΔT across the condensate

$= T_v - T_s$

= 112.8 - 90.33

= 22.5°F

Heat flux through the SS 304 plate

$$\frac{Q}{A} = K \frac{\Delta T}{\Delta x}$$

$$= \frac{9.0 * [90.33 - (90.33 - 1 * 26.292]}{1/12}$$

$$= 2840 \text{ Btu/hr} \cdot \text{ft}^2$$

Condensing heat transfer coefficient

$$h = \frac{Q/A}{\Delta T} = \frac{2840}{22.5}$$

$$= 126 \text{ Btu/hr} \cdot \text{ft}^2 \cdot {}^\circ\text{F}$$

Prediction based on Bernhardt's equation

$$h_o = \left[\frac{k_{lo}^3\ \rho_{lo}^2\ g\ \lambda_o}{4\mu_{lo}(T_v - T_s)\ x}\right]^{1/4} * \left[1 + 0.68\ \frac{Cp_{lo}\ (T_v - T_s)}{\lambda_o}\right]^{1/4}$$

$$= \left[\frac{0.038^3 * 97.81^2 * 32 * 3600^2 * 63.18}{4 * 1.646 * 22.5 * 23/12}\right]^{1/4}$$

$$* \left[1 + 0.68 * \frac{0.212 * 22.5}{61.18}\right]^{1/4}$$

$$= 84.48\ \mathrm{Btu/hr{\cdot}ft^2{\cdot}{}^0F}$$

$$h_w = \left[\frac{k_{lw}^3\ \rho_{lw}^2\ g\ \lambda_w}{4\ \mu_{lw}\ (T_v - T_s)\ x}\right]^{1/4} * \left[1 + 0.68\ \frac{Cp_{lw}\ (T_v - T_s)}{\lambda_w}\right]^{1/4}$$

$$= \left[\frac{0.37^3 * 61.8^2 * 32 * 3600^2 * 1030}{4 * 1.525 * 22.5 * 23/12}\right]^{1/4}$$

$$* \left[1 * 0.68 * \frac{1 * 22.5}{1030}\right]^{1/4}$$

$$= 751.4\ \mathrm{Btu/hr{\cdot}ft^2{\cdot}{}^0F}$$

$$h_{NU} = \frac{h_o\ v_o + h_w\ v_w}{v_o + v_w}$$

$$= \frac{84.48 * 95 + 751.4 * 0.1}{95 + 0.1}$$

$$= 85.2\ \mathrm{Btu/hr{\cdot}ft^2{\cdot}{}^0F}$$

Vapor velocity calculation

Total mass flowrate for R-113

$$= (95 + 320) * \frac{60}{1000} * \frac{97.81}{28.32}$$

$$= 86.0\ \mathrm{lb/hr}$$

Total mass flowrate for water

$$= (0.1 + 3.4) * \frac{60}{1000} * \frac{61.8}{28.32}$$

$$= 0.458\ \mathrm{lb/hr}$$

Local R-113 vapor flowrate

$$= \frac{[320 + 95 * (1 - 23/26)] * 60 * 97.81}{1000 * 28.32}$$

= 68.58 lb/hr

Local water vapor flowrate

$$= \frac{[3.4 + 0.1 * (1 - 23/26)] * 60 * 61.8}{1000 * 28.32}$$

= 0.4467 lb/hr

Vapor channel cross section: 2" x 1 1/8"

Local vapor velocity

$$= \frac{68.58/0.4604 + 0.4467 * 245}{3600 * (2 * 1.125)/144}$$

= 4.6 ft/sec

Prediction based on Boyko-Kruzhilin equation

Total mass velocity G_T

$$= \frac{(86 + 0.458)}{2 * 1.125} * 144$$

$= 5533.3\ lb/hr \cdot ft^2$

Equivalent diameter for vapor flow channel

$$D_{eq} = 4 * \frac{C.S.\ Area}{perimeter}$$

$$= 4 * \frac{2 * 1.125}{(2 + 1.125) * 2}$$

= 1.44 inch

Total condensate Reynolds number

$$Re_T = \frac{G_T \; D_{eq}}{\mu_l}$$

$$= \frac{5533.3 * 1.44/12}{1.6459}$$

$$= 403.43$$

Condensate Prandtl number

$$Pr_l = \frac{Cp_l \; \mu_l}{k_l}$$

$$= \frac{0.2125 * 1.6459}{0.03822}$$

$$= 9.151$$

Local quality

$$x = \frac{68.58 + 0.4467}{86.0 + 0.458}$$

$$= 0.7984$$

$$h_{BK} = \frac{k_l}{D_{eq}} * 0.024 * Re_T^{0.8} * Pr_l^{0.43} * [1 * \frac{\rho_l - \rho_v}{\rho_v} x]^{1/2}$$

$$= \frac{0.03822}{1.44/12} * 0.024 * 403.43^{0.8} * 9.151^{0.43}$$

$$* [1 + \frac{97.77 - 0.4285}{0.4285} * 0.7984]^{1/2}$$

$$= 32.5 \text{ Btu/hr} \cdot \text{ft}^2 \cdot {}^{\circ}\text{F}$$

Prediction based on Akers-Turner equation 1

R-113 condensing heat load

$$Q_o = \frac{19.69 * 63.18}{26 * 2/144} = 3198.9 \text{ Btu/hr}\cdot\text{ft}^2$$

Water condensing heat load

$$Q_w = \frac{0.0131 * 1030}{26 * 2/144} = 34.7 \text{ Btu/hr}^2\cdot\text{ft}$$

Total condensing heat load

$$= 3230.3 \text{ Btu/hr}\cdot\text{ft}^2$$

Condensing heat transfer coefficient

$$H_{AT1} = \frac{Q_o\ h_o + Q_w\ h_w}{Q_o + Q_w}$$

$$= \frac{34.7 * 751.4 + 3198.9 * 84.48}{3230.3}$$

$$= 91.7 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

Prediction based on Akers-Turner equation 2

Local condensate loading

$$\Gamma = \frac{(19.69 + 0.0131) * 23/26}{2/12}$$

$$= 104.58 \text{ lb/hr}\cdot\text{ft}$$

Weight averaged mixture liquid density

$$\rho_l = \frac{w_w\ \rho_{lw} + w_o\ \rho_{lo}}{w_w + w_o}$$

$$= \frac{0.0131 * 61.8 + 19.69 * 97.81}{19.69 + 0.0131}$$

$$= 97.79 \text{ lb/ft}^3$$

Condensing heat tranfer coefficient

$$h_{AT2} = 1.47 \left(\frac{4\Gamma}{\mu_o}\right)^{-1/3} \left(\frac{k_l^3 \rho_l^2 g}{\mu_o^2}\right)^{1/3}$$

$$= 1.47 \left(\frac{4 * 104.58}{1.646}\right)^{-1/3} * \left(\frac{0.03822^3 * 97.79^2 * 32 * 3600^2}{1.646^2}\right)^{1/3}$$

$$= 100.7 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^0\text{F}$$

Local condensate Reynolds number

$$= \frac{4\Gamma}{\mu_l}$$

$$= \frac{4 * 104.58}{1.6459}$$

$$= 254.16$$

Local condensation number

$$= h \left[\frac{k_l^3 \rho_l^2 g}{\mu_l^2}\right]^{-1/3}$$

$$= 0.2904$$

SOURCE CODE

```
$JOB
C23456789
      DIMENSION T(70,31),NRUN(70),DLOC(5),NV(5),NF(5),NM(5),NB(5)
      DIMENSION XT(3,5),C(3),D(3),FRLOC(5)
      DIMENSION FPR(40),WPR(40),FSE(40),WSE(40),COLPR(40),COLSE(40)
      DIMENSION XPP(200),YPP(200),XP(40),YP(40)
      DATA KW,KXYP/6,0/
      DATA NV/1,17,18,19,20/
      DATA NF/16,5,7,14,13/
      DATA NM/2,4,8,10,11/
      DATA NB/3,6,9,12,15/
      DATA DLOC/3.,8.0,13.0,18.0,23.0/
      DATA XT/0.016,0.0151,0.0123,0.0144,0.0144,-0.0013,0.024,0.0335,-0.
     #0113,0.0144,0.0229,0.0019,0.0323,0.0256,0.0008/
      DATA LF/11/
C     DATA XT/15*0.0/
      DO 90 I=1,5
90    FRLOC(I)=(3.0+(I-1.0)*5.0)/26.0
      MPT=0
10    K=MPT+1
      READ(5,*,END= 99)NRUN(K)
      MPT=MPT+1
      READ(5,*) (T(MPT,I),I=2,10)
      READ(5,*) (T(MPT,I),I=11,20)
      READ(5,*)FPR(MPT),WPR(MPT),FSE(MPT),WSE(MPT),COLPR(MPT),COLSE(MP
     #T),T(MPT,28),T(MPT,29),T(MPT,30),T(MPT,31)
      COLSE(MPT)=COLSE(MPT)*2.7/100.
      T(MPT,1)=(T(MPT,17)+T(MPT,18)+T(MPT,19)+T(MPT,20))/4.0
      GO TO 10
99    HNF=397.9
      HNW=3570.7
      C(1)=0.25
      C(2)=0.5
      C(3)=0.75
      DO 100 NST=1,5
      J1=NV(NST)
      J2=NF(NST)
      J3=NM(NST)
      J4=NB(NST)
      WRITE(6,21)
 21   FORMAT(1H1,////////,'  ')
      WRITE(6,110)NST,(XT(J,NST),J=1,3)
110   FORMAT(18X,'STATION NUMBER ',I3,/,13X,3F10.5,//,10X,'RUN',3X,
     #'TV',4X,'TF',4X,'TM',4X,'TB',2X,'PRIMARY',25X,'AUXILIARY',/,39X,'F
     #RE',2X,'WAT',5X,'COOLANT ',13X,'FRE',2X,'WAT',9X,'COOLANT',/,
     # 49X,' GPM    IN    OUT',20X,'GPM    IN    OUT',/)
      DO 120 I=1,MPT
 120  WRITE(6,130)NRUN(I),T(I,J1),T(I,J2),T(I,J3),T(I,J4),FPR(I),WPR(I)
     #,COLPR(I),T(I,28),T(I,29),FSE(I),WSE(I),COLSE(I),T(I,30),T(I,31)
 130  FORMAT(9X,I3,6(1X,F5.1),1X,F4.2,2(1X,F5.1),5X,2(1X,F5.1),2X,F4.2,2
     #(1X,F5.1))
100   CONTINUE
      DO 60 NST=1,5
      J1=NV(NST)
      J2=NF(NST)
      J3=NM(NST)
      J4=NB(NST)
      WRITE(6,21)
      WRITE(6,20)NST
20    FORMAT(18X,' STATION NUMBER',I3,/,8X,' RUN',2X,'DT',6X,'H',5X
     #,'HNU',5X,'HBK',4X,'Q/A LOC  CONDENS.   ','VAP VEL',5X,'X',6X,'Y
     #',4X,'HAT1',5X,'HAT2',/)
      DO 40 I=1,MPT
      SYXW=0.0
      SY=0.0
      SI=3
      SXW=0.0
      SXWXW=0.0
      D(1)=T(I,J2)
      D(2)=T(I,J3)
      D(3)=T(I,J4)
      DO 30 J=1,3
```

```
      SYXW=SYXW+D(J)*(C(J)-XT(J,NST))
      SY=SY+D(J)
      SXW=SXW+C(J)-XT(J,NST)
30    SXWXW=SXWXW+(C(J)-XT(J,NST))**2
      A1=(SYXW*SI-SY*SXW)/(SI*SXWXW-SXW*SXW)
      A0=(SY-A1*SXW)/SI
      DT=T(I,J1)-A0
      Q=-A1*108.0
      H=-A1*108.0/DT
      HNFRE=HNF*((1.+0.68*0.212*DT/63.18)/(DLOC(NST)*DT))**0.25
      HNWAT=HNW*((1.+0.68*DT/1030.0)/(DLOC(NST)*DT))**0.25
      HNU=(HNFRE*FPR(I)+HNWAT*WPR(I))/(FPR(I)+WPR(I))
C
      FPRW=FPR(I)*0.2072
      FSEW=FSE(I)*0.2072
      WPRW=WPR(I)*0.1309
      WSEW=WSE(I)*0.1309
      VAPFRE=FSE(I)+(1.0-FRLOC(NST))*FPR(I)
      VAPWAT=WSE(I)+(1.0-FRLOC(NST))*WPR(I)
      VAPVEL=(VAPFRE*0.2072*2.172 + VAPWAT*0.1309*245.)/(3600.0*
     #2.0*1.125/144.0)
      CONDL = (0.038*FPRW + 0.37*WPRW) / (FPRW+WPRW)
C     CONDL=( 0.038*FPR(I) + 0.37*WPR(I) )/
C    #( FPR(I) + WPR(I) )
      VISCL=(FPRW+WPRW)/( FPRW/1.646 + WPRW/1.525 )
      CPL=(FPRW*0.212+WPRW)/(FPRW+WPRW)
      RHOV=(FPRW+WPRW)/(FPRW*2.172+WPRW*245.0)
      RHOL=(FPR(I)*97.81+WPR(I)*61.8)/(FPR(I)+WPR(I))
      RET=(FPRW+FSEW+WPRW+WSEW)*1.44/12.0/VISCL*144.0/2.25
      PRL=CPL*VISCL/CONDL
      QUAL=(VAPFRE*0.2072+VAPWAT*0.1309)/(FPRW+FSEW+WPRW+WSEW)
      GR3=(1.0+QUAL*(RHOL-RHOV)/RHOV)**0.5
      HBK=0.024*RET**0.8*PRL**0.43*GR3*CONDL/1.44*12.0
      QCON=(FPR(I)*13.09+WPR(I)*134.86)/56.0*144.0
      HAT1=( HNFRE*FPR(I)*13.09*(1.0+0.68*0.212*DT/63.18)**0.25 +
     # HNWAT*WPR(I)*134.86*(1.0+0.68*DT/1030.0)**0.25 )/56.0*144.0/QCON
      RHOLW = (97.81*FPRW+61.8*WPRW)/(FPRW+WPRW)
      ATG1 = 24.0*(WPRW+FPRW)*FRLOC(NST)/1.646
      ATG2 = CONDL**3*RHOLW**2*32.0*3600.0**2/1.646**2
      HAT2 = 1.47*(ATG2/ATG1)**(1./3.)
      YP(I)=H*(VISCL**2/ (CONDL**3*RHOL*(RHOL-RHOV)*32.*3600.*3600.) )**
     #(1.0/3.0)
      XP(I)=(WPRW+FPRW)*24.0*FRLOC(NST)/VISCL
      WRITE(LF,200) XP(I),YP(I)
200   FORMAT(1X,F10.4,1X,F8.4)
      WRITE(6,50)NRUN(I),DT,H,HNU,HBK,Q,QCON,VAPVEL,XP(I),YP(I),HAT1,
     #HAT2
40    CONTINUE
      WRITE(LF,210)
210   FORMAT('   ')
 50   FORMAT(9X,I3,1X,F5.1,3(1X,F6.0),2(2X,F7.0),5X,F6.2,3X,F6.2,2X,F6.4
     #,3X,F6.0,2X,F6.0)
60    CONTINUE
      WRITE(6,21)
      STOP
      END
$ENTRY
133
86.2,79.5,83.1,89.3,76.7,87.8,81.3,74.6,80.7
77.5,73.7,85.0,86.1,70.9,92.6,110.6,110.5,110.7,110.3
88.3,0.33,140.0,0.567,3.4,61.0,61.4,62.3,61.5,64.6
134
85.1,78.5,82.4,88.5,76.9,86.5,80.2,73.5,79.2
76.5,72.4,83.0,84.3,69.7,91.0,109.4,109.2,109.4,109.1
85.0,0.42,82.5,0.5,3.8,61.0,62.3,63.0,62.3,64.5
135
85.3,78.7,82.2,88.3,75.9,86.6,80.2,73.4,79.2
76.0,72.3,83.2,84.3,69.6,91.0,109.3,109.0,109.3,108.9
81.0,0.54,49.0,0.58,3.8,60.0,62.7,63.4,62.7,64.3
136
88.2,81.3,85.0,91.6,78.3,89.4,82.6,75.7,81.6
78.1,74.4,85.5,87.2,71.5,94.9,113.3,113.1,113.2,113.3
```

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98.75,0.225,360.0,5.5,3.4,61.0,62.7,63.5,62.7,70.0
137
88.0,81.0,84.7,91.2,77.9,89.1,82.3,75.3,81.2
77.1,73.9,85.0,86.5,71.0,94.4,112.7,112.5,112.7,112.8
95.0,0.14,320.0,3.4,3.4,64.0,62.9,63.7,62.9,69.1
138
88.4,81.5,85.0,91.4,78.3,89.5,82.7,75.7,81.4
78.0,74.1,85.3,86.6,71.1,94.4,112.3,112.0,112.3,112.5
95.0,0.14,375.0,3.3,3.4,62.0,63.5,64.3,63.4,69.6
139
88.1,81.6,85.4,91.5,79.1,89.5,83.2,76.5,82.3
79.1,75.5,86.3,87.8,72.8,94.8,112.5,112.2,112.3,112.1
95.0,0.25,256.67,4.67,3.0,53.0,63.2,64.0,63.2,69.3
140
87.8,81.2,84.8,91.0,78.4,89.1,82.6,75.9,81.4
78.2,74.5,85.3,86.5,71.8,94.0,111.2,111.0,111.1,111.1
87.5,0.25,164.0,1.24,3.2,58.0,63.2,64.0,63.2,67.8
141
88.6,81.9,85.7,91.9,79.1,89.5,83.0,76.3,81.9
78.5,75.9,85.6,87.1,71.9,94.2,111.7,111.5,111.6,111.5
88.75,0.25,200.0,1.2,3.2,56.0,63.9,64.7,63.9,69.4
142
98.3,94.2,96.8,100.9,92.8,99.6,95.5,91.0,94.7
92.3,90.2,97.0,98.2,88.2,102.5,113.2,113.1,113.2,113.1
61.25,0.0,295.0,1.3,2.6,63.0,81.9,82.5,64.2,70.1
143
98.7,94.5,97.1,101.1,93.1,99.7,95.6,91.0,94.5
92.3,90.1,96.9,97.8,88.1,102.2,112.7,112.7,112.8,112.7
62.0,0.06,270.0,2.5,2.5,61.0,82.7,83.4,64.8,70.4
144
98.8,94.5,96.9,100.9,92.9,99.5,95.4,90.9,94.3
92.0,90.0,96.4,97.5,88.1,101.8,112.3,112.2,112.4,112.4
58.75,0.0,280.0,2.5,2.4,61.0,84.5,85.0,65.4,70.8
145
91.6,85.5,88.5,94.6,82.6,92.5,86.3,80.0,85.0
81.4,78.4,88.6,90.4,75.4,98.2,114.8,114.6,114.8,114.6
93.75,0.225,485.0,6.1,2.0,56.0,64.2,65.4,64.3,72.3
146
92.7,86.5,89.6,95.7,83.5,93.3,86.9,80.3,85.3
81.5,78.4,88.7,90.5,75.1,98.5,114.9,114.5,114.9,114.9
87.5,0.05,525.0,11.5,2.0,54.0,65.3,66.6,65.3,74.0
147
91.6,85.4,88.6,94.7,82.3,92.5,86.0,79.4,84.4
80.6,77.5,87.7,89.5,74.2,97.0,113.9,113.7,114.0,114.1
83.75,0.025,375.0,6.0,2.2,63.0,65.9,66.9,65.8,72.6
148
89.1,82.7,86.3,92.2,80.3,90.7,84.6,78.3,83.3
80.7,77.4,87.4,88.9,75.0,95.6,112.3,112.0,112.1,111.8
90.0,0.175,295.0,3.3,3.6,52.0,65.9,66.6,66.0,72.6
$IBSYS
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RESULTS

Nomenclature for Data Printout and Results

TV	vapor temperature, °F
TF	front thermocouple, °F
TM	middle thermocouople, °F
TB	back thermocouple, °F
PRIMARY	data for test cell
AUXILIARY	data for auxiliary condenser
FRE	R-113 condensate flow rate, ml/min
WAT	water condensate flow rate, ml/min
GPM	coolant flow rate, gal/min
IN	coolant inlet temperature, °F
OUT	coolant outlet temperature, °F
DT	ΔT_f, °F
H	condensing coefficient, Btu/hr-ft^2-°F
HNU	H calculated by Nusselt equation
HBK	H calculated by Boyko-Kruzhilin equation
Q/A LOC	local heat flux, Btu/hr-ft^2
CONDENS	heat flux based on condensate flow rate, Btu/hr-ft^2
VAP VEL	vapor velocity, ft/sec
X	local condensate Reynolds number
Y	local condensation number
HAT1	H calculated by Akers-Turner equation 1
HAT2	H calculated by Akers-Turner equation 2

STATION NUMBER 1

0 01600 0 01510 0 01230

RUN	TV	TF	TM	TB	PRIMARY FRE	PRIMARY WAT	PRIMARY COOLANT GPM	PRIMARY COOLANT IN	PRIMARY COOLANT OUT	AUXILIARY FRE	AUXILIARY WAT	AUXILIARY COOLANT GPM	AUXILIARY COOLANT IN	AUXILIARY COOLANT OUT
133	110 5	92.6	86 2	79 5	88 3	0 3	3 40	61 4	62 3	140 0	0 6	1 65	61 5	64 6
134	109 3	91 0	85 1	78 5	85 0	0 4	3 80	62 3	63 0	82 5	0 5	1 65	62 3	64 5
135	109.1	91 0	85.3	78.7	81.0	0.5	3.80	62.7	63.4	49.0	0.6	1.62	62.7	64.3
136	113 2	94 9	88 2	81 3	98.8	0 2	3.40	62.7	63.5	360.0	5.5	1 65	62 7	70 0
137	112 7	94 4	88 0	81.0	95.0	0 1	3.40	62.9	63 7	320 0	3 4	1 73	62 9	69 1
138	112 3	94 4	88 4	81 5	95 0	0 1	3 40	63 5	64 3	375 0	3 3	1 67	63 4	69 6
139	112 3	94 8	88 1	81 6	95 0	0 3	3 00	63 2	64 0	256 7	4 7	1 43	63 2	69 3
140	111 1	94 0	87 8	81 2	87 5	0 3	3 20	63 2	64 0	164 0	1 2	1 57	63 2	67 8
141	111.6	94.2	88.6	81.9	88.8	0.3	3.20	63 9	64 7	200 0	1.2	1.51	63 9	69.4
142	113.1	102 5	98.3	94 2	61 3	0 0	2 60	81 9	82.5	295.0	1.3	1.70	64 2	70 1
143	112 7	102 2	98.7	94.5	62.0	0.1	2 50	82.7	83.4	270 0	2.5	1 65	64.8	70 4
144	112 3	101 8	98 8	94 5	58 8	0 0	2 40	84 5	85 0	280 0	2 5	1 65	65 4	70 8
145	114 7	98 2	91 6	85 5	93 8	0 2	2 00	64 2	65 4	485.0	6 1	1 51	64 3	72 3
146	114 8	98 5	92 7	86 5	87 5	0 1	2 00	65 3	66 6	525 0	11 5	1 46	65 3	74 0
147	113 9	97.0	91.6	85.4	83 8	0.0	2.20	65.9	66 9	375 0	6.0	1.70	65.8	72 6
148	112 0	95.6	89.1	82.7	90.0	0 2	3.60	65.9	66.6	295.0	3.3	1.40	66 0	72 6

STATION NUMBER 2

0 01440 0 01440 -0 00130

RUN	TV	TF	TM	TB	PRIMARY FRE	PRIMARY WAT	PRIMARY COOLANT GPM	PRIMARY COOLANT IN	PRIMARY COOLANT OUT	AUXILIARY FRE	AUXILIARY WAT	AUXILIARY COOLANT GPM	AUXILIARY COOLANT IN	AUXILIARY COOLANT OUT
133	110 6	89 3	83 1	76 7	88 3	0 3	3 40	61 4	62 3	140 0	0 6	1 65	61 5	64 6
134	109 4	88 5	82 4	76 9	85 0	0 4	3 80	62 3	63 0	82 5	0 5	1 65	62 3	64 5
135	109.3	88.3	82.2	75.9	81.0	0.5	3 80	62.7	63 4	49.0	0.6	1.62	62.7	64 3
136	113 3	91.6	85 0	78 3	98 8	0.2	3 40	62 7	63.5	360 0	5 5	1.65	62 7	70.0
137	112 7	91 2	84 7	77 9	95 0	0 1	3.40	62.9	63 7	320 0	3.4	1 73	62 9	69 1
138	112 3	91 4	85 0	78 3	95 0	0 1	3 40	63 5	64 3	375 0	3 3	1 67	63 4	69 6
139	112 5	91.5	85 4	79 1	95 0	0 3	3 00	63 2	64 0	256 7	4 7	1 43	63 2	69 3
140	111 2	91 0	84 8	78 4	87 5	0 3	3 20	63 2	64 0	164 0	1 2	1 57	63 2	67 8
141	111.7	91 9	85 7	79.1	88.8	0 3	3.20	63 9	64 7	200 0	1 2	1 51	63 9	69 4
142	113.2	100.9	96.8	92.8	61.3	0 0	2 60	81 9	82 5	295 0	1.3	1 70	64 2	70 1
143	112.7	101.1	97 1	93 1	62 0	0.1	2 50	82 7	83.4	270.0	2.5	1.65	64 8	70 4
144	112 3	100 9	96 9	92 9	58 8	0 0	2 40	84 5	85 0	280 0	2 5	1 65	65 4	70 8
145	114 8	94 6	88 5	82 6	93 8	0 2	2 00	64 2	65 4	485 0	6 1	1 51	64 3	72 3
146	114 9	95 7	89 6	83 5	87 5	0 1	2.00	65 3	66 6	525.0	11 5	1 46	65 3	74 0
147	113.9	94.7	88.6	82.3	83.8	0.0	2.20	65.9	66.9	375 0	6.0	1.70	65.8	72.6
148	112 3	92.2	86 3	80 3	90 0	0 2	3 60	65 9	66 6	295 0	3.3	1 40	66 0	72 6

STATION NUMBER 3

0 02400 0 03350 -0 01130

RUN	TV	TF	TM	TB	PRIMARY FRE	PRIMARY WAT	PRIMARY COOLANT GPM	PRIMARY COOLANT IN	PRIMARY COOLANT OUT	AUXILIARY FRE	AUXILIARY WAT	AUXILIARY COOLANT GPM	AUXILIARY COOLANT IN	AUXILIARY COOLANT OUT
133	110 5	87 8	81 3	74 6	88 3	0 3	3 40	61 4	62 3	140 0	0 6	1 65	61 5	64 6
134	109 2	86 5	80 2	73 5	85 0	0 4	3 80	62 3	63 0	82 5	0 5	1 65	62 3	64 5
135	109.0	86.6	80.2	73 4	81.0	0.5	3.80	62.7	63 4	49.0	0 6	1.62	62.7	64.3
136	113.1	89.4	82.6	75.7	98 8	0 2	3 40	62 7	63.5	360 0	5 5	1.65	62 7	70 0
137	112 5	89.1	82.3	75 3	95.0	0 1	3.40	62 9	63 7	320 0	3 4	1 73	62 9	69 1
138	112 0	89 5	82 7	75 7	95 0	0 1	3 40	63 5	64 3	375 0	3 3	1 67	63 4	69 6
139	112 2	89 5	83 2	76 5	95 0	0 3	3 00	63 2	64 0	256 7	4 7	1 43	63 2	69 3
140	111 0	89 1	82 6	75 9	87 5	0 3	3 20	63 2	64 0	164 0	1 2	1 57	63 2	67 8
141	111.5	89.5	83.0	76 3	88.8	0.3	3 20	63.9	64 7	200.0	1.2	1.51	63 9	69 4
142	113.1	99.6	95.5	91.0	61.3	0.0	2.60	81 9	82 5	295.0	1.3	1 70	64 2	70.1
143	112.7	99.7	95.6	91 0	62 0	0 1	2 50	82.7	83.4	270 0	2.5	1.65	64 8	70 4
144	112 2	99 5	95 4	90 9	58 8	0 0	2 40	84 5	85 0	280 0	2 5	1 65	65 4	70 8
145	114 6	92 5	86 3	80 0	93 8	0 2	2 00	64 2	65 4	485 0	6 1	1 51	64 3	72 3
146	114 5	93 3	86 9	80 3	87 5	0 1	2 00	65 3	66 6	525 0	11 5	1 46	65 3	74 0
147	113.7	92.5	86.0	79 4	83 8	0.0	2.20	65 9	66.9	375.0	6.0	1.70	65.8	72.6
148	112 0	90.7	84 6	78.3	90.0	0.2	3 60	65 9	66 6	295.0	3.3	1.40	66 0	72.6

STATION NUMBER 4

0 01440 0 02290 0 00190

RUN	TV	TF	TM	TB	PRIMARY FRE	PRIMARY WAT	PRIMARY COOLANT GPM	PRIMARY COOLANT IN	PRIMARY COOLANT OUT	AUXILIARY FRE	AUXILIARY WAT	AUXILIARY COOLANT GPM	AUXILIARY COOLANT IN	AUXILIARY COOLANT OUT
133	110 7	86 1	80 7	73 7	88 3	0 3	3 40	61 4	62 3	140 0	0 6	1 65	61 5	64 6
134	109 4	84 3	79 2	72 4	85 0	0 4	3 80	62 3	63 0	82 5	0 5	1 65	62 3	64 5
135	109.3	84.3	79 2	72 3	81.0	0 5	3 80	62 7	63 4	49 0	0 6	1.62	62.7	64.3
136	113 2	87.2	81.6	74 4	98 8	0.2	3 40	62.7	63 5	360.0	5 5	1 65	62.7	70 0
137	112.7	86 5	81.2	73.9	95.0	0.1	3.40	62.9	63.7	320.0	3 4	1.73	62 9	69 1
138	112 3	86 6	81 4	74 1	95 0	0 1	3 40	63 5	64 3	375 0	3 3	1 67	63 4	69 6
139	112 3	87 8	82 3	75 5	95 0	0 3	3 00	63 2	64 0	256 7	4 7	1 43	63 2	69 3
140	111 1	86 5	81 4	74 5	87 5	0 3	3 20	63 2	64 0	164 0	1 2	1 57	63 2	67 8
141	111.6	87.1	81.9	75 9	88 8	0.3	3.20	63 9	64.7	200 0	1.2	1.51	63 9	69 4
142	113.2	98.2	94.7	90.2	61.3	0.0	2.60	81 9	82.5	295 0	1.3	1.70	64 2	70.1
143	112.8	97 8	94 5	90 1	62 0	0 1	2 50	82 7	83 4	270 0	2.5	1.65	64.8	70 4
144	112 4	97 5	94 3	90 0	58 8	0 0	2 40	84.5	85 0	280 0	2 5	1 65	65 4	70 8
145	114 8	90 4	85 0	78 4	93 8	0 2	2 00	64.2	65 4	485 0	6 1	1 51	64 3	72 3
146	114 9	90 5	85 3	78 4	87 5	0 1	2 00	65 3	66 6	525 0	11 5	1 46	65 3	74 0
147	114.0	89 5	84.4	77.5	83.8	0.0	2.20	65.9	66.9	375 0	6 0	1.70	65.8	72 6
148	112 1	88.9	83.3	77.4	90 0	0.2	3.60	65.9	66 6	295.0	3 3	1 40	66 0	72.6

STATION NUMBER 5

0 03230 0 02560 0 00080

RUN	TV	TF	TM	TB	PRIMARY FRE	PRIMARY WAT	PRIMARY COOLANT GPM	PRIMARY COOLANT IN	PRIMARY COOLANT OUT	AUXILIARY FRE	AUXILIARY WAT	AUXILIARY COOLANT GPM	AUXILIARY COOLANT IN	AUXILIARY COOLANT OUT
133	110 3	85 0	77 5	70 9	88 3	0 3	3 40	61 4	62 3	140 0	0 6	1 65	61 5	64 6
134	109 1	83 0	76 5	69 7	85 0	0 4	3 80	62 3	63 0	82 5	0 5	1 65	62 3	64 5
135	108.9	83 2	76.0	69 6	81.0	0.5	3.80	62.7	63 4	49 0	0 6	1.62	62.7	64.3
136	113 3	85.5	78.1	71.5	98 8	0.2	3 40	62 7	63 5	360.0	5 5	1 65	62 7	70.0
137	112.8	85.0	77.1	71.0	95 0	0.1	3.40	62.9	63 7	320 0	3.4	1.73	62.9	69 1
138	112 5	85 3	78 0	71 1	95 0	0 1	3 40	63 5	64 3	375 0	3 3	1 67	63 4	69 6
139	112 1	86 3	79 1	72 8	95.0	0 3	3 00	63 2	64 0	256 7	4 7	1 43	63 2	69 3
140	111 1	85 3	78 2	71 8	87 5	0 3	3 20	63 2	64 0	164 0	1 2	1 57	63 2	67 8
141	111.5	85 6	78.5	71.9	88.8	0.3	3 20	63.9	64.7	200 0	1.2	1.51	63.9	69 4
142	113 1	97 0	92 3	88.2	61.3	0.0	2 60	81 9	82 5	295.0	1 3	1 70	64 2	70 1
143	112.7	96 9	92 3	88 1	62 0	0.1	2 50	82 7	83 4	270 0	2.5	1 65	64.8	70.4
144	112 4	96 4	92 0	88 1	58 8	0 0	2 40	84 5	85 0	280 0	2 5	1 65	65 4	70 8
145	114 6	88 6	81 4	75 4	93 8	0 2	2 00	64 2	65 4	485 0	6 1	1 51	64 3	72 3
146	114 9	88 7	81 5	75 1	87 5	0 1	2 00	65 3	66 6	525 0	11.5	1 46	65 3	74 0
147	114 1	87.7	80.6	74.2	83.8	0.0	2.20	65 9	66.9	375 0	6 0	1.70	65 8	72 6
148	111.8	87.4	80 7	75.0	90.0	0 2	3.60	65 9	66 6	295.0	3 3	1.40	66.0	72 6

STATION NUMBER 1

RUN	DT	H	HNU	HBK	Q/A LOC	CONDENS	VAP VEL	X	Y	HAT1	HAT2
133	11.8	238.	169	24.	2809.	3087.	2 23	30.86	0.5417	214	206
134	12.4	217.	169	19.	2680	3007.	1 76	29 73	0.4904	226	210
135	12.3	215.	171.	17.	2637	2914	1.57	28 36	0.4818	247	215.
136	12 0	243	167	41	2916	3402	6 83	34 48	0 5580	195	197
137	12 0	240	166	36	2873	3246	5 24	33 15	0 5533	184	199
138	11 7	236	166	40	2766	3246	5 62	33 15	0 5425	185	199
139	11 4	249.	169.	33.	2830.	3284	5.51	33 18	0.5689	201.	200
140	11 1	247.	170.	25.	2744.	3032.	2 76	30 56	0 5654	206	206
141	11 5	230	169	28	2637	3074	3 04	31 00	0 5251	203.	205.
142	6 8	261	188	31	1780	2062	3 53	21 35	0 6059	189	229
143	6 8	242	189	30	1651	2108	4 05	21 63	0 5576	203	229
144	6 9	226	187	29	1565	1978	4 08	20 48	0 5250	188	232
145	10 7	255	171	49.	2723	3234.	8.14	32 73	0.5835	201	201
146	10.7	241	169	49	2573.	2963.	11 40	30 51	0 5582	177	204
147	11.4	218.	166.	38	2487	2828	7 03	29.20	0 5052	171	206.
148	10.5	264	172	35	2766	3090	4 97	31 41	0 6060	196	203

STATION NUMBER 2

RUN	DT	H	HNU	HBK	Q/A LOC	CONDENS.	VAP VEL	X	Y	HAT1	HAT2
133	15.6	169.	124.	23.	2638.	3087	2 06	82.29	0.3854	157	149
134	15.8	154.	124.	18	2427	3007	1 58	79.28	0.3480	167.	152
135	15.4	169.	127.	15.	2596.	2914.	1 38	75.64	0 3787	183.	155
136	15 7	178	122	40	2785	3402	6 65	91 94	0 4073	143	142
137	15 4	180	122.	36	2785	3246	5 08	88 40	0 4153	136	144
138	14 9	184	123	39	2743	3246	5 46	88 40	0 4230	137	144
139	15 4	169.	123.	32.	2597	3284.	5.34	88 47	0.3867	147	144
140	14 5	182.	125.	24.	2638.	3032	2 60	81.50	0.4166	151	149
141	14 0	192.	126	27.	2681.	3074	2 87	82 66	0 4393	152	148
142	8 7	196	139	30	1696	2062	3 44	56 94	0 4544	139	165
143	8 0	210	142	29	1675	2108	3 95	57 67	0 4840	153	165
144	7 8	215	142	29	1675	1978	3 99	54 61	0 4991	143	167
145	14 8	170	124.	49	2512.	3234.	7 97	87.29	0.3884	146.	145
146	13 7	187.	125.	48.	2554.	2963	11 26	81.37	0 4316	131	147
147	13.6	191	125	37	2596	2828	6.89	77 87	0.4435	128.	149.
148	14 7	169	124	34	2492	3090	4 81	83 77	0 3890	142	146

STATION NUMBER 3

RUN	DT	H	HNU	HBK	Q/A LOC	CONDENS	VAP VEL	X	Y	HAT1	HAT2
133	17.4	153.	107.	22.	2655	3087.	1 89	133 72	0.3482	135.	127
134	17.4	150	108.	17	2616.	3007	1 40	128.83	0 3401	144.	129
135	17.0	156.	110	14	2657.	2914	1 20	122 91	0 3499	158	132.
136	18 2	152	104	39	2755	3402	6 48	149 40	0 3477	122	121
137	17 8	156	104	35	2776	3246	4 92	143 65	0 3589	116	122
138	16 9	164	106	39	2776	3246	5 30	143 65	0 3780	118	122
139	17 4	150.	106.	31	2616	3284.	5.17	143.76	0.3443	126	123
140	16.6	160.	107.	24.	2655	3032	2 44	132.43	0 3667	130.	126
141	16.7	159	107	27.	2655.	3074.	2.71	134.32	0 3646	129.	126
142	10 0	174	119	29	1732	2062	3 35	92 52	0 4034	119	140
143	9 4	186	121	29	1752	2108	3 85	93 72	0 4303	130	140
144	9 2	189	121	28	1732	1978	3 90	88 75	0 4386	122	142
145	17.1	147.	106.	48	2514.	3234	7.80	141 85	0.3378	125.	123.
146	15 9	164	106.	47	2615.	2963	11 12	132.23	0.3798	112	125
147	15.9	166.	106.	37.	2635.	2828	6 76	126 54	0 3837	109	127
148	16 3	153	107	33	2494	3090	4 65	136 13	0 3521	123	125

STATION NUMBER 4

RUN	DT	H	HNU	HBK	Q/A LOC	CONDENS	VAP VEL	X	Y	HAT1	HAT2
133	18.7	140.	97.	21	2617.	3087.	1.72	185 16	0.3178	122	114
134	19 4	129	97.	16	2512.	3007.	1.23	178.38	0 2921	130.	116
135	19.3	131.	98	13.	2533.	2914.	1.02	170 19	0 2945	142.	119.
136	20 0	135	94	38	2701	3402	6 30	206 86	0 3103	110	109
137	20 2	132	93	34	2660	3246	4 76	198 90	0 3037	104	110
138	19 7	134	94	38	2640	3246	5 14	198 90	0 3086	105	110
139	18 7	138.	96.	30.	2594.	3284.	4 99	199 05	0 3169	114	110.
140	18 9	134.	96.	23	2533	3032.	2 28	183 37	0.3067	116	113
141	19.3	122.	95	26	2361.	3074.	2 55	185.98	0.2793	115.	113.
142	11 2	150	106	29	1688	2062	3 25	128 11	0 3491	107	126
143	11 3	143	107	28	1625	2108	3 75	129 76	0 3309	115	126
144	11 3	140	106	28	1583	1978	3 81	122 88	0 3243	107	128
145	18 8	135.	96	47.	2531.	3234.	7.63	196.40	0.3086	113	111.
146	18 7	137.	94.	47.	2554.	2963.	10 98	183 08	0 3168	99	112
147	18 8	135.	94	36	2533	2828	6 63	175 20	0 3126	97.	114
148	18 0	135	96	32	2422	3090	4 49	188 49	0 3094	110	112

STATION NUMBER 5

RUN	DT	H	HNU	HBK	Q/A LOC	CONDENS	VAP VEL	X	Y	HAT1	HAT2
133	19 8	145.	90.	20.	2862.	3087	1 55	236.59	0.3294	114	105.
134	20.7	131	90	15.	2702.	3007	1 05	227.93	0.2955	120	107
135	20 4	136.	91.	12	2761	2914	0 83	217.46	0.3040	132.	109
136	22 3	127	86	37	2842	3402	6 12	264 32	0 2923	101	100
137	22 5	126	85	33	2840	3246	4 60	254.15	0 2910	96	101
138	21 5	134	86	37	2883	3246	4 98	254 15	0 3082	96	101
139	20.5	134.	88.	29	2740	3284.	4.82	254.35	0.3057	105	102
140	20.5	134	88	22.	2741.	3032.	2.12	234.30	0.3059	107	104
141	20.5	136.	88	25.	2782.	3074	2.38	237.64	0.3108	107	104.
142	12 7	141	97	28	1786	2062	3 16	163 69	0 3276	98	116
143	12 3	145	98	28	1786	2108	3 65	165 81	0 3348	106	116
144	12 7	132	97	27	1685	1978	3 72	157 01	0 3070	98	118
145	20.9	128.	88	46	2678.	3234	7 46	250.96	0.2939	103.	102.
146	20.9	132.	86.	46.	2761.	2963	10 84	233.94	0 3063	91	103
147	21.1	130	86	35	2740	2828	6 50	223 87	0 3013	89	105
148	19 6	129	89	32	2516	3090	4 34	240 85	0 2953	102	103

APPENDIX H

ERROR PROPAGATION ANALYSIS

APPENDIX H

The error propagation analysis is done to evaluate the effect of errors in measurement on the calculated quantities, such as condensing coefficient, heat flux, etc. Due to the nature of the properties of the systems studied, steam condensation calculations are most suceptible to large errors in calculated quantities.

The following analysis is done for Run #35, at Station 1. Worst case scenario is assumed while assuming measurement errors. The results are compared with calculations in Appendix C, which assume no errors in the measurements.

Quantity	Measurement	Maximum Error	Assumed Measurement
T_{vapor}	209.1°F	± 0.3°F	208.8°F
T_{front}	185.2°F	± 0.3°F	185.5°F
T_{middle}	164.7°F	± 0.3°F	164.4°F
T_{back}	143.0°F	± 0.3°F	142.7°F
Condensate flow rate	41.6 ml/min	± 2 ml/min	43.6 ml/min

Evaluated hot surface temperature

T_s = 205.47°F

ΔT across the condensate = 3.33°F

Heat flux through the SS 304 plate

$\frac{Q}{A}$ = 9180 Btu/hr·ft^2

Condensing heat transfer coefficient

$h = 2757$ Btu/hr•ft^2•°F

Condensate Reynolds number

= 21.43

Local condensation number

= 0.4915

Quantity	% Error (Propagated)
h	25.5
Re_x	4.8
N_{co_x}	25.5

VITA

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