SIZING OF REFLUX

CONDENSERS

By

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PREFACE

The purpose of this study is to present the basis design equations required to size a reflux condenser. A computer program is also written to handle the condensation of both a pure vapor and a multicomponent vapor.

Two examples are also presented. The results look reasonable, but lack of experimental data prevents a more quantitative test of the program.

I wish to express my sincere thanks to Dr. Kenneth J. Bell for his advice and guidance and to the School of Chemical Engineering for the financial support offered to me.

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NOMENCLATURE

A	cross sectional area, ft^2
a	acceleration force field, ft^2/hr^2
b_1	numerical coefficient used in evaluating heat transfer coefficient, dimensionless
B	constant relating interfacial liquid velocity throughout the condensate film, dimensionless
C_p	specific heat, Btu/lbm ^oF
dQ_{sv}, dQ_T	local differential values of sensible load and total heat load, respectively, Btu/hr
D	inside tube diameter, inches
D_c	critical tube diameter, inches
f	shear stress multiplied by g_c, lbm/ft-hr^2
FC	fraction condensed, dimensionless
F_o	wall shear stress multiplied by g_c, lbm/ft-hr^2
Fr	Froude number based on total flow rate and local densities, dimensionless
F_1, F_2	correlation factors defined in equations 2.29 and 2.31, dimensionless
G	superficial vapor mass flux (or mass velocity), lbm/ft hr^2
g	acceleration of gravity, ft/hr^2
g_c	conversion factor 4.175×10^8, lbm ft/lbf hr^2
$\overline{h_c}$	average heat transfer coefficient, Btu/hr ft^2 ^oF

$h_c(z)$	local heat transfer coefficient, Btu/hr ft^2 ^{o}F
h_{sv}	vapor phase heat transfer coefficient, Btu/hr ft^2 ^{o}F
k	thermal conductivity, Btu/hr ft ^{o}F
k_i	equilibrium constant, dimensionless
L	superficial liquid mass flow rate, lbm/hr ft^2
L_T	length of tube, ft
L/F	liquid to feed ratio, dimensionless
M_i	mole fraction in feed of component, dimensionless
N_{tubes}	number of tubes, dimensionless
OD	outer tube diameter, inches
P	pressure, psia
Pr_ℓ	Prandtl number, dimensionless
q''	heat flux, Btu/hr ft^2
Q_T	heat recovered per tube, Btu/hr
Q_{Total}	total heat recovered in all tubes, Btu/hr
Re_c	condensate Reynolds number, dimensionless
Re_{LT}	Reynolds number of the condensate at the bottom of the tube, dimensionless
Re_{Lz}	local Reynolds number of the condensate at any point along the tube, dimensionless
Re_T	Reynolds number based on total flow rate and local vapor density (Eq. 3.6), dimensionless
R_{fi}, R_{fo}	inside and outside fouling resistances, respectively, hr ft^2 ^{o}F/Btu
S	circumference, ft
T	temperature, ^{o}F

T_1, T_2	temperature of the coolant at the inlet and outlet, respectively, ^oF
U_i	overall heat transfer coefficient from vapor liquid interface to the collant, Btu/hr ft^2 ^oF
u^*	frictional velocity, ft/sec
V_f	flooding velocity, ft/sec
V_ℓ	mean liquid film velocity, ft/sec
$V_{\ell i}$	interfacial velocity, ft/sec
V_v	vapor velocity, ft/sec
$V_{v, o}$	outlet vapor velocity, ft/sec
W	mass flow rate, lbm/hr
x	local quality, dimensionless
x_i	mole fraction of liquid of component i, dimensionless
y_i	mole fraction of vapor of component i, dimensionless
Δz	length increment, ft
Z	ratio of $\frac{dQ_{sv}}{dQ_T}$, dimensionless

Subscripts

a	gravity term
c	condensate
cool	coolant
f	friction
m	momentum
ℓ	liquid
sat	saturation
v	vapor
w	wall

Greek Letters

α	Zivi void fraction, dimensionless
β	forces due to interfacial shear stress (Eq. 2.4), lb_f/ft^2
Δ	difference, finite
ε	small number
η	force due to gravity on liquid, lb_f/ft^2
θ	angle
λ	latent heat of condensation, Btu/lbm
μ	viscosity, absolute, lbm/hr ft
ρ	density, lbm/ft^3
σ	surface tension, dynes/cm
	term in equation 2.3, dimensionless
τ_i	interfacial shear stress, lb_f/ft^2
τ_o	wall shear stress, lb_f/ft^2

CHAPTER I

INTRODUCTION

Condensation occurs when a vapor comes in contact with a surface whose temperature is below the saturation temperature at the existing partial pressure of the vapor. However, in case of multi-component condensation, the dew-point temperature must be used and it should be noted that the composition of the condensate formed is different from the composition of the vapor mixture at the same temperature and total pressure.

Vertical condensers with upward flow of vapor have not been as thoroughly investigated as those with downward flow of vapor. But sometimes it is necessary to maintain a liquid mixture at a given temperature, while carrying on an exothermic chemical reaction. In order to do so, a volatile liquid can be vaporized in the reactor and returned as a liquid at a continuous rate from the reflux condenser (Figure 1). Pressure and therefore the temperature in the reactor can be controlled by controlling the coolant flow rate and temperature to the condenser.

One of the major problems in a reflux or knock-back condenser (Figure 2) is the flooding of tubes. When the vapor flow is countercurrent to the condensate flow, the following effects are observed (1). Figures 3a-3e show the changes taking place in a tube.

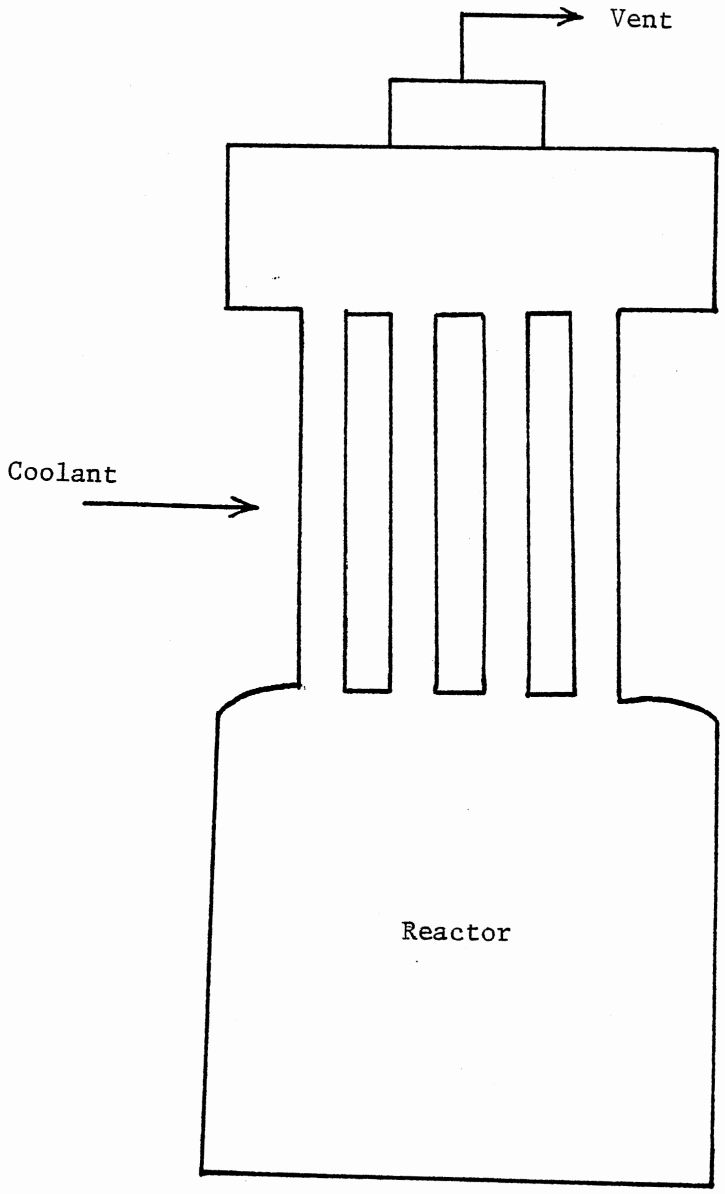


Figure 1. Reflux Condensation.

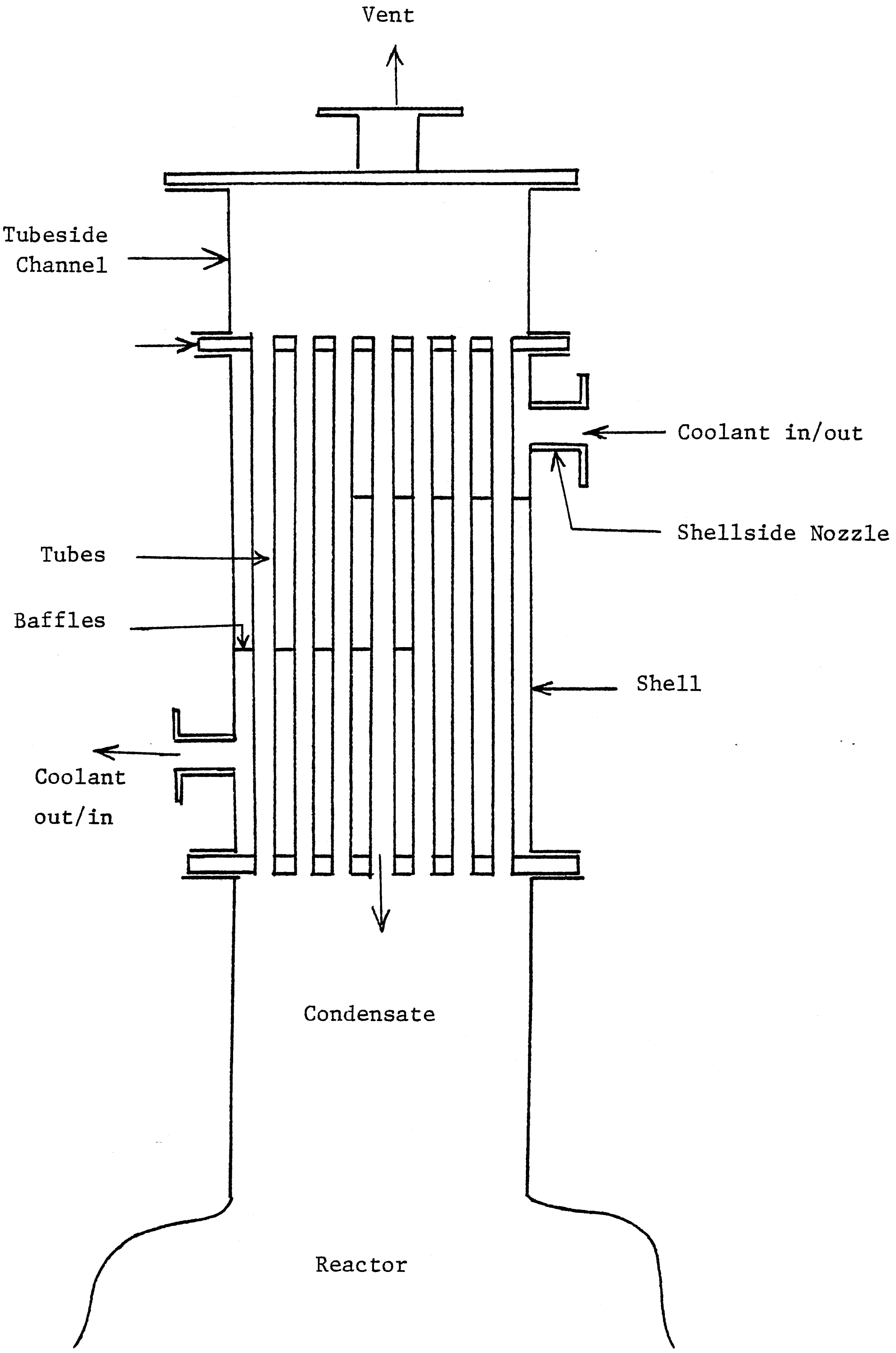


Figure 1. A Reflux Condenser

1. At low vapor velocities, the condensate runs down the walls of the tubes, thus giving reflux operation (Figure 3.a).

2. Increase of vapor velocity will result in the appearance of waves, especially near the inlet. This is because of the appearance of early turbulence at high vapor velocities (Figure 3.b).

3. Further increase in the vapor velocity causes the waves to bridge across the tube, but the flux rate remains constant (Figure 3.c).

4. The flooding point is said to have reached when the vapor velocity is high enough to eject the liquid out of the tube from the top. A dramatic rise in the pressure drop will occur as a result (Figure 3.c).

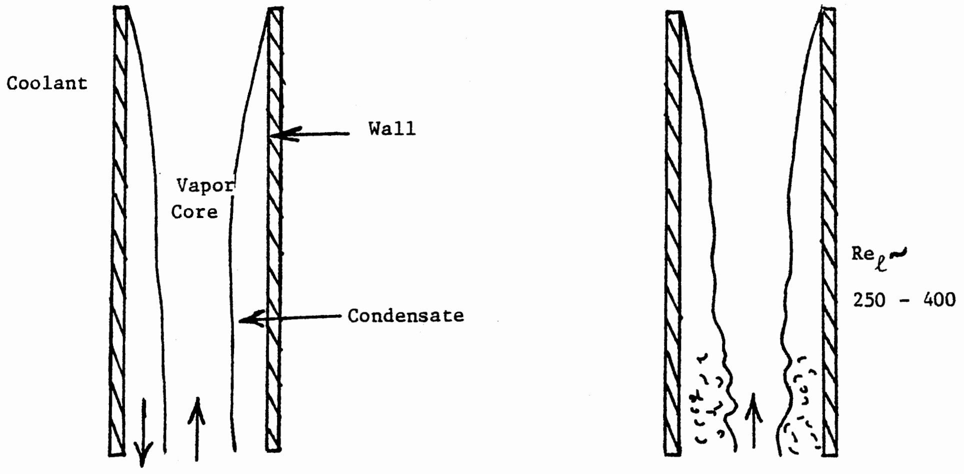
5. Further increase in the vapor flow will result in a climbing film annular flow (Figure 3.e).

In general, it is necessary to operate below the flooding velocity in order to avoid undesirable pressure fluctuations. Several correlations have been proposed to calculate the flooding velocity. The highest liquid and gas rates occur at the entrance of the tubes in a reflux condenser and hence, the flooding point is at the inlet (Figure 4).

English et al. (2) showed experimentally that a taper on the tube end permits higher vapor rates to the exchanger before flooding takes place.

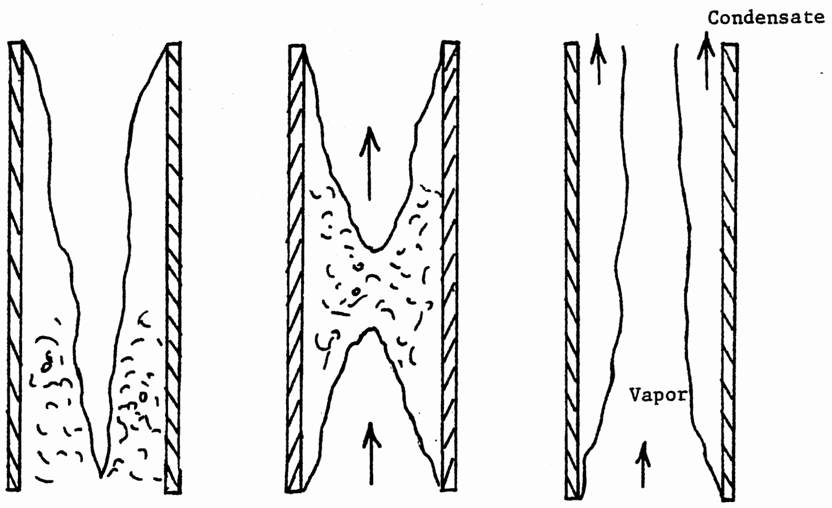
The purpose of this study is to outline the basic design equations required to size a reflux condenser. First, the flooding point is computed, followed by mass and heat balance. The method of calculating the heat transfer coefficient will be discussed.

In case of condensation of multicomponent mixtures, the approximate design procedure as outlined by Bell and Ghaly (3) will be used. A



a. Smooth downward flow of condensate. (Total reflux.)

b. Appearance of turbulence near entrance.



c. Bridging of waves across tube.

d. Vapor pushing out condensate. (No reflux.)

e. Upward cocurrent annular flow. (Climbing film.)

Figure [redacted]. Mechanism of Flooding.

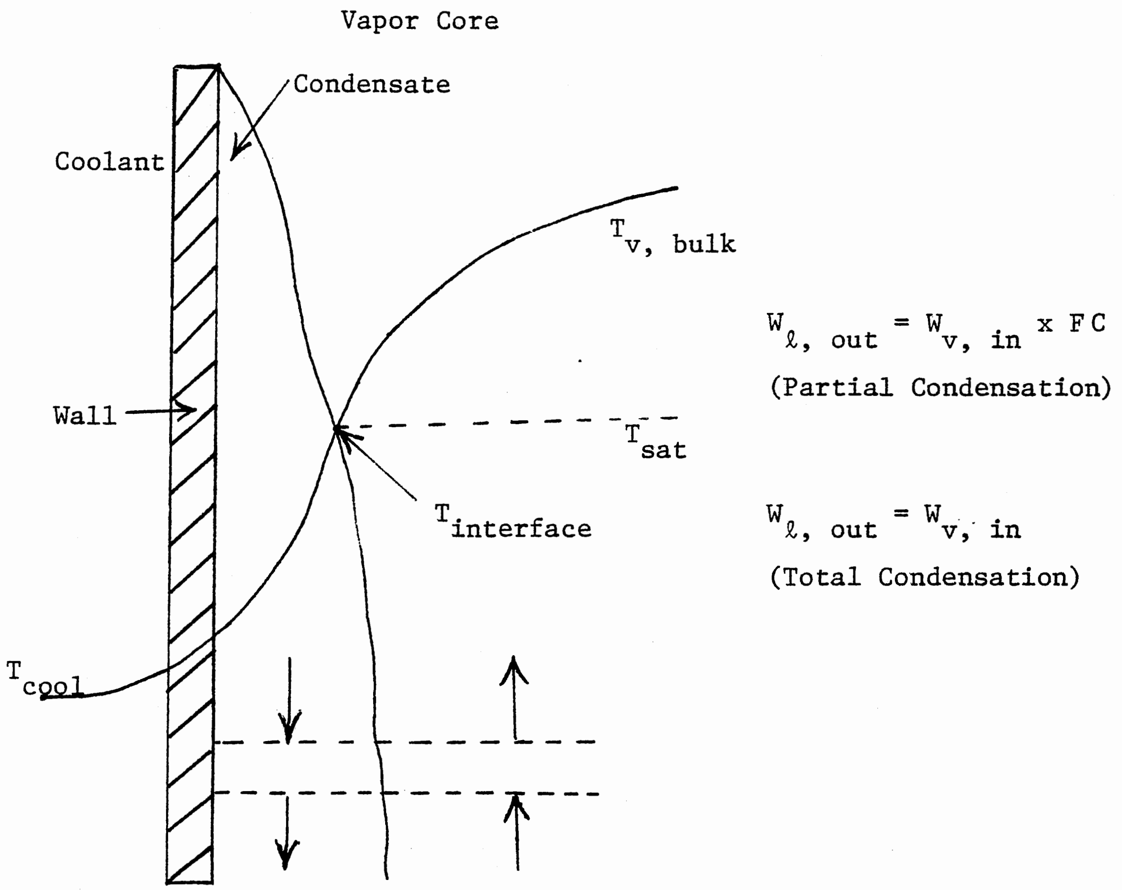


Figure 4. Flow Rates at Inlet.

computer program to handle the condensation of both a pure vapor as well as a multicomponent vapor is presented in Appendix B. The program handles saturated vapors only. In the case of multicomponent condensation, the thermodynamic and physical properties are read as input data. They are calculated using the GPA*SIM (4) program.

CHAPTER II

LITERATURE REVIEW

Filmwise condensation on a vertical surface was first studied by Nusselt (5). Although the original work was published in German, the details of his analysis are readily available in a number of books, e.g., Jakob (6). The details of the analysis will not be presented here. Only the important results will be mentioned.

One of the assumptions that Nusselt made was that even in the presence of high vapor velocities the entire condensate film remained in laminar flow. This will not affect the heat transfer coefficient strongly as long as the velocities are low (laminar region). However, in case of vapor shear, turbulence may appear at Reynolds number as low as 250-300 as reported by Carpenter and Colburn (7).

In the absence of vapor shear, the Nusselt Equation for the average condensate heat transfer coefficient is:

$$\bar{h}_c = 1.47 \left[\frac{k_\ell^3 \, \rho_\ell (\rho_\ell - \rho_v) \, g}{\mu_\ell^2} \right]^{1/3} Re_c^{-1/3} \tag{2.1}$$

In the present model, the point equation is used.

$$h_c(z) = \left(\frac{k_\ell^3 \, \rho_\ell (\rho_\ell - \rho_v) \, \lambda g}{4\mu_\ell \, (T_{sat} - T_w) \, z} \right)^{1/4} \tag{2.2}$$

Condensation heat transfer coefficients for turbulent flow were studied by Kirkbride (8), but Colburn (9) contributed a more fundamental analysis for the mean coefficient which is generally represented in graphical form (Figure 5). The break at a condensate Reynolds Number of about 2100 shows the point at which the film is presumed to become turbulent.

Dukler (10) developed new equations for velocity and temperature distribution based on the expressions proposed by Deissler (11) for the eddy diffusivity for momentum and heat. This accounted for turbulent fluctuations close to the wall. His equations require numerical solutions with the aid of a computer. [Although he developed his model for the case of cocurrent down flow of vapor and liquid, it can be modified for countercurrent-flow cases.] This can be done by taking negative values of the parameter β as defined by Dukler (Equation 2.3). β represents the forces due to interfacial shear and η represents the force due to gravity acting on the liquid.

$$\sigma^3 + \frac{\beta}{\eta^{2/3}} \sigma^2 - 1 = 0 \qquad (2.3)$$

$$\beta = \frac{Fr\; g_\ell^{1/3} \; \rho_\ell^{2/3}}{2\mu_\ell^{2/3}} \qquad (2.4)$$

The shear stress distribution is given by:

$$\frac{\tau}{\tau_o} = 1 - \frac{\sigma^3}{\eta} y^+ \qquad (2.5)$$

where $y^+ = (u^* y/\nu)$ (2.6)

and u^* is usually called the friction velocity

$$u^* = \left(\frac{\tau_o g_c}{\rho} \right)^{1/2} \qquad (2.7)$$

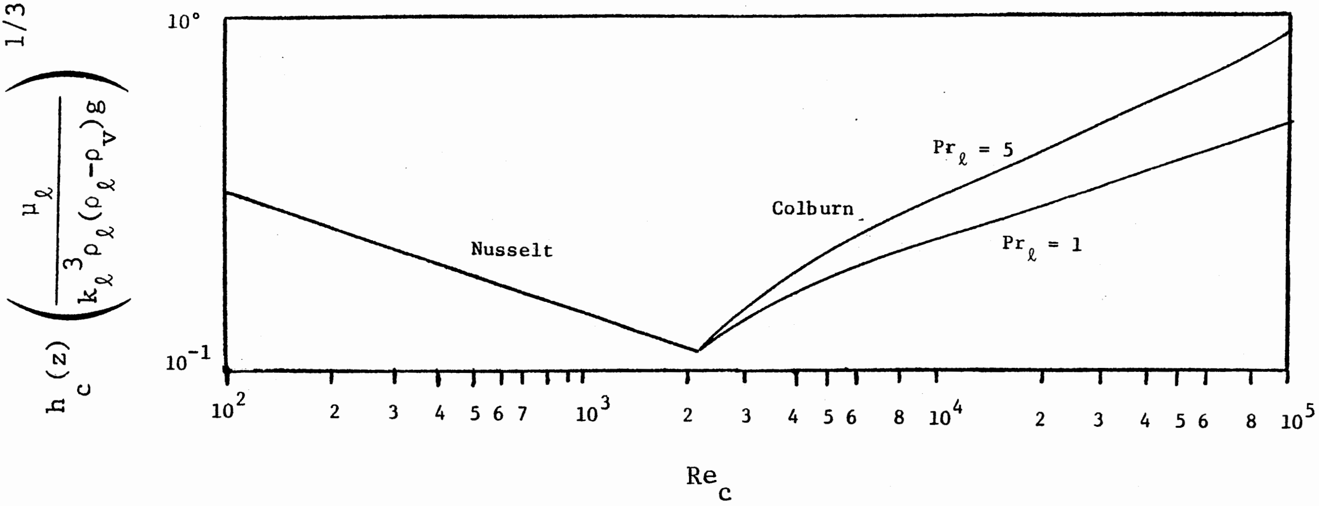


Figure 5. Correlation for Condensation on a Vertical Surface - No Vapor Shear. (9)

Average condensing heat transfer coefficients were calculated from the point values and the results obtained agree with Nusselt's values in teh Nusselt region and approximately agree with Colburn's equation in the turbulent region. Figures 6 and 7 show the average heat transfer coefficients obtained from Dukler's analysis for the case of no interfacial shear and for the case of positive interfacial shear, respectively. In both cases, Prandtl number is equal to 1.0.

The equation governing Figure 6 is

$$\bar{h}_c \left(\frac{\mu_\ell^2}{\rho_\ell \, g \, k_\ell^3} \right)^{1/3} = \frac{Re_{LT}}{\displaystyle\int_0^{Re_{\ell T}} \frac{dRe_{Lz}}{h_c(z)\left(\frac{\mu_\ell^2}{\rho_\ell \, g \, k_\ell^3} \right)^{1/3}}} \qquad (2.8)$$

where

Re_{LT} = Reynolds number of the condensate at the bottom of the tube

Re_{Lz} = Local Reynolds number at any point along the tube.

However, Equation 2.8 cannot be used as such for the case with interfacial shear because β varies due to the variation in the pressure gradient. Hence, Dukler developed a new relation for β.

$$\beta = A(Re_{LT} - Re_{Lz})^{1/4} \, Re_{Lz}^{\;0.4} \qquad (2.9)$$

$$A = \frac{0.25 \, \mu_\ell^{1.173} \, \mu_v^{0.16}}{g^{2/3} \, D^2 \, \rho_\ell^{0.443} \, \rho_v^{0.78}} \qquad (2.10)$$

Then a plot of local Reynolds number Re_c, vs. the corresponding local coefficient term is made and the average coefficient is obtained by integrating the same expression as before.

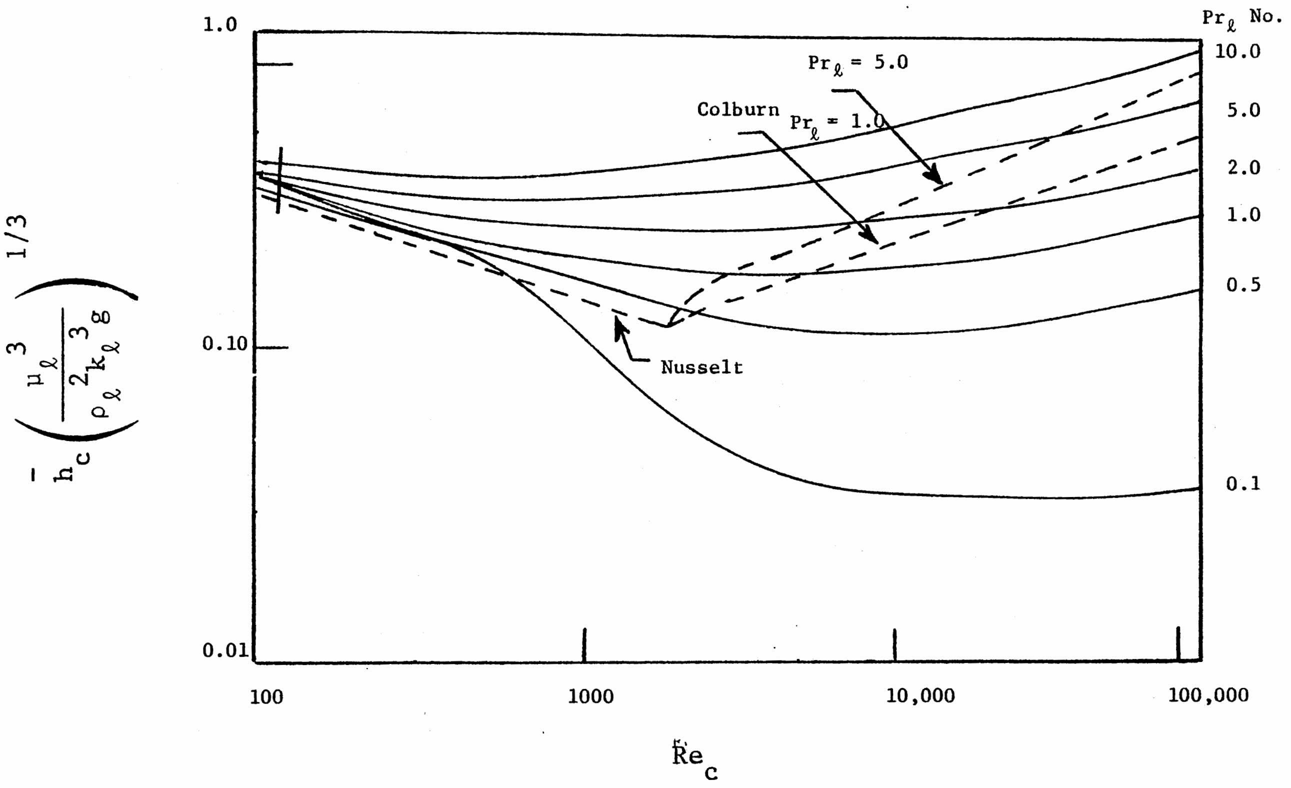


Figure 6. Average Coefficient, No Interfacial Shear. (10)

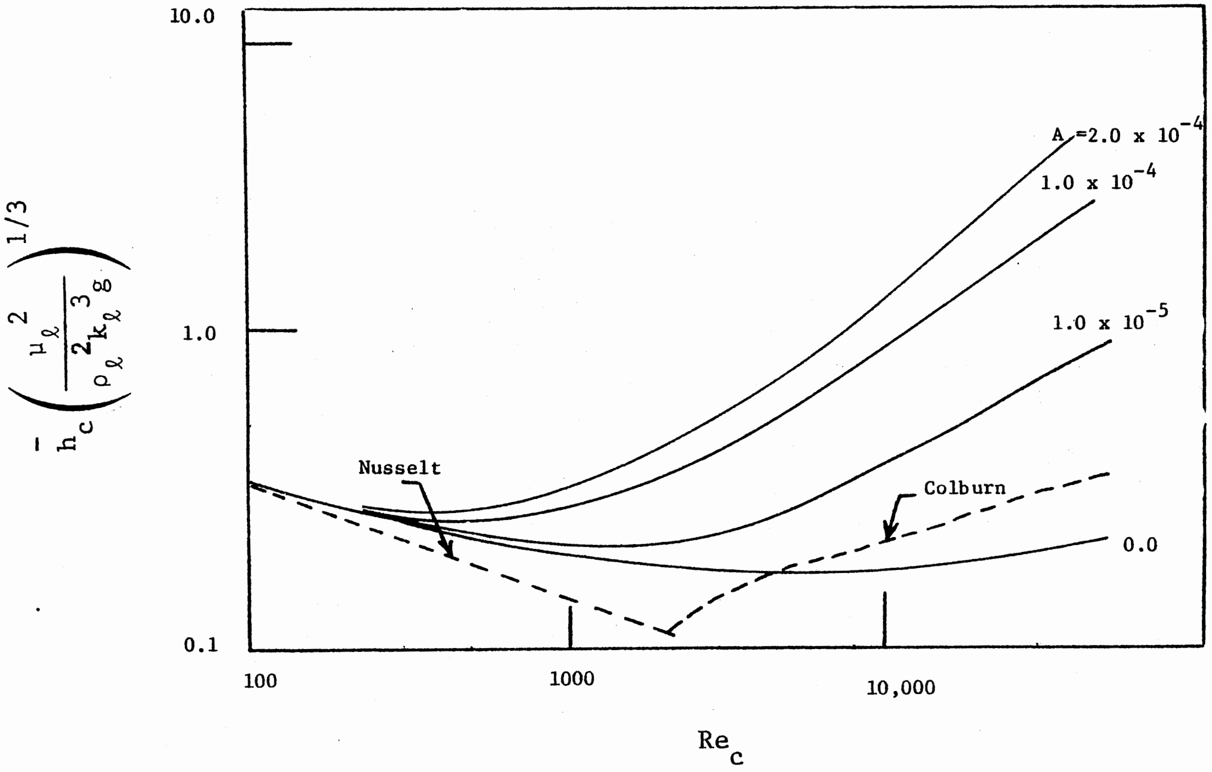


Figure 7. Average Coefficient for Pr = 1.0 (10)

Several objections were raised to Dukler's analysis (12).

a. The velocity distribution he used was obtained from experiments in pipes with a different shear stress distribution.

b. For y^+ greater than 20, the molecular conductivity term is neglected with respect to eddy conductivity.

Although the above discrepancies are overcome in the analysis presented by Kunz and Yerazunis (13) their results do not vary very much from those of Dukler's.

Jakob, et al. (6) considered only the case of downward flowing vapor. They conducted experiments in a vertical condenser tube. The results obtained are shown in Figures 8 and 9. They are a result of 171 experiments with saturated steam at 100^oC and 325^oC, atmospheric pressure, and with an entrance velocity of the vapor, V_v, from 10 to 80 m/sec. The heat flux q" is plotted versus $(T_{sat} - T_w)$ with V_v as the parameter. The conclusions that they drew were:

1. If the temperature difference is large, i.e., $(T_{sat} - T_w)$ is large, then the heat transfer is always larger than that predicted by Nusselt's theory. This could be due to the dropwise condensation on the vapor end of the cooling surface which accounts for more heat transmitted on the top of the tube, or possibly due to turbulent films (due to significant vapor shear effects).
2. For small values of temperature difference, the experiments with saturated steam resulted in smaller values of heat transferred than those predicted by Nusselt's theory. This is probably due to some air trapped in the tube.

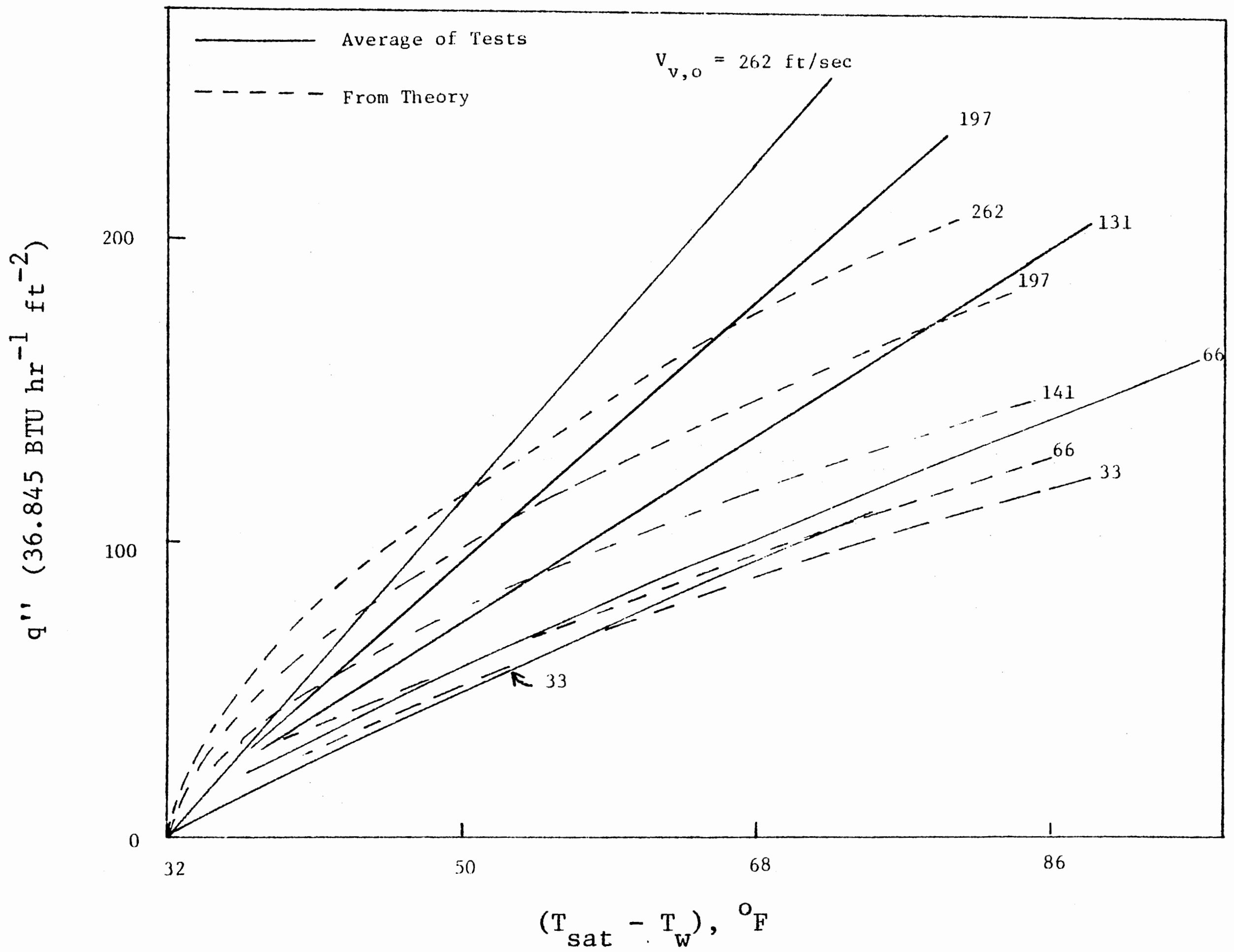


Figure 8. Heat Transfer by Condensation of Saturated Steam at Atmospheric Pressure. (6)

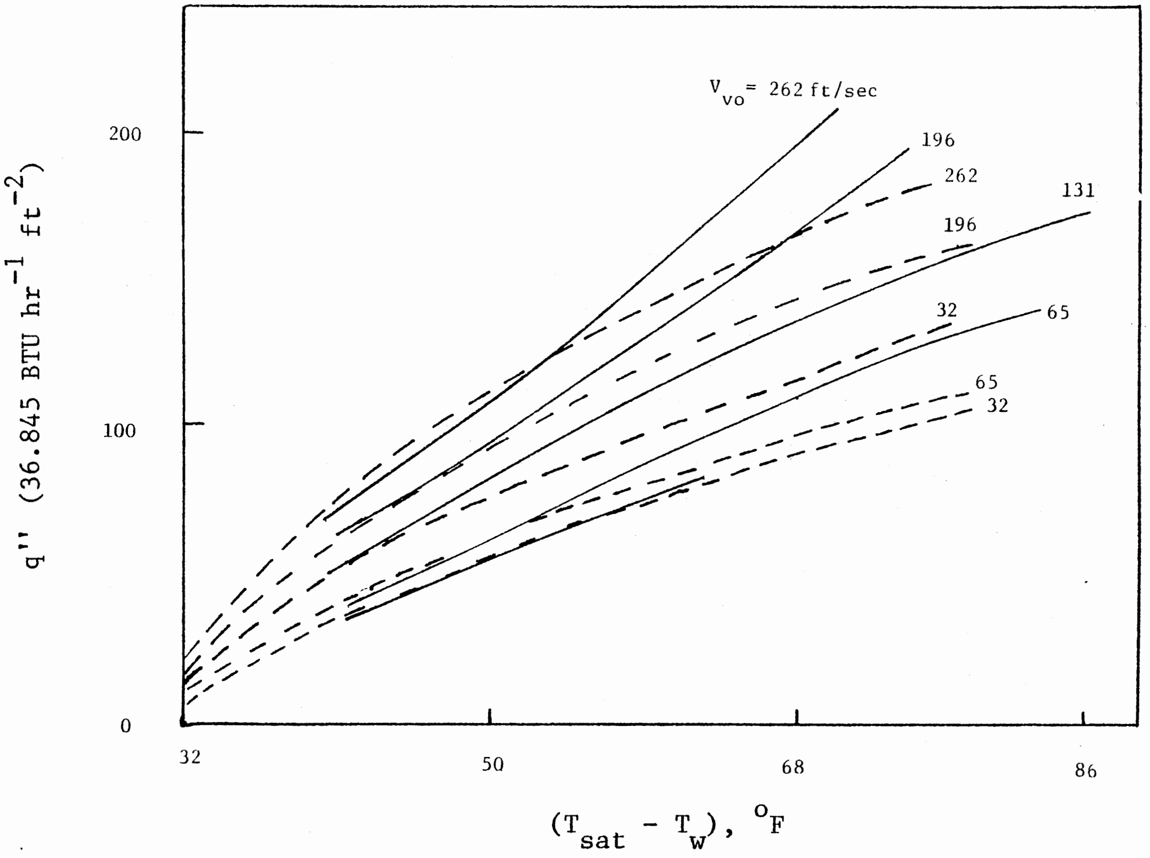


Figure 9. Heat Transfer by Condensation of Superheated Steam at Atmospheric Pressure and 325° C. (6)

The empirical equation which Jakob et al. (6) recommend to represent their experimental results are:

1. Saturated Steam

$$q'' = 2.713(3400 + 100\ V_{v,\ o})(T_{sat} - T_w)(1{\cdot}21/L)^{1/3} \qquad (2.11)$$

2. Superheated Steam

$$q'' = 2.713\ (3500 + 51\ V_{v,\ o})(T_{sat} - T_w)(1{\cdot}21/L)^{1/3} \qquad (2.12)$$

where q" is Btu/hr ft^2.

As mentioned earlier, Carpenter and Colburn (7) studied vapor shear effects, and they found that the heat transfer coefficients were considerably larger than those obtained in the absence of vapor shear. The major force acting on the condensate film is the interfacial shear. The equation for local heat transfer coefficient that they presented was:

$$\frac{h_c(z)\mu_\ell}{k_\ell\ \rho_\ell^{\frac{1}{2}}} = 0.045\ (Pr_\ell)^{\frac{1}{2}}\ \tau_w^{\frac{1}{2}} \qquad (2.13)$$

where τ_w is the wall shear stress. In calculating the wall shear stress account must be taken of the interfacial shear and the gravitational momentum of the condensing vapor and the effect of the vapor mass transfer on the interfacial shear stress must be included. However in the analysis by Carpenter and Colburn (7), the gravitational and momentum terms were neglected and the wall shear stress was equated to the interfacial shear stress in evaluating an average heat transfer coefficient:

$$\frac{\bar{h}_c\mu_\ell}{k_\ell\rho_\ell^{\frac{1}{2}}} = 0.065\ (Pr_\ell)^{\frac{1}{2}}\ \tau_i^{\frac{1}{2}} \qquad (2.14)$$

where

$$\tau_i = f_i \frac{\overline{W_v}^2}{2\rho_v} \tag{2.15}$$

and

$$\overline{W_v} = \left[\frac{W_{v,\,in}^2 + W_{v,\,in} W_{v,out} + W_{v,\,out}^2}{3}\right]^{\frac{1}{2}} \tag{2.16}$$

Soliman, Schuster and Berenson (14) improved the Carpenter and Colburn analysis and suggested a better equation for local heat transfer coefficient with the help of further experimental data (Figure 10).

$$\frac{h_{c(z)} \mu_\ell}{k_\ell \rho_\ell^{\frac{1}{2}}} = 0.036 \,(Pr_\ell)^{0.65} F_o^{\frac{1}{2}} \tag{2.17}$$

where F_o, the wall shear stress, is affected by three factors; gravity F_a, momentum F_m, and friction F_f.

$$F_o = F_a + F_m + F_f \tag{2.18}$$

F_f, the frictional shear stress exists at the vapor liquid interface and acts in a direction opposite to flow.

$$F_f = f_V \frac{S_v}{S} \left(1 + \frac{A_\ell}{A_v}\right) \tag{2.19}$$

where

$$f_v = \frac{g_c A_v}{S_v} \left(\frac{\Delta P}{\Delta z}\right)_{TPF} \tag{2.20}$$

$$F_m = \frac{DG^2}{4\rho_v} \left(\frac{\Delta x}{\Delta z}\right) \left[a_1 \left(\frac{\rho_v}{\rho_\ell}\right)^{1/3} + a_2 \left(\frac{\rho_v}{\rho_\ell}\right)^{2/3} + \dots\ a_5 \left(\frac{\rho_v}{\rho_\ell}\right)^{5/3}\right] \tag{2.21}$$

The void fraction correlation due to Zivi (15) is used in the derivation of this equation. The coefficients a_1, a_2...., a_5 are:

$a_1 = 2x - 1 - \beta x$

$a_2 = 2(1 - x)\ \beta$

$a_3 = 2(1 - x - \beta + \beta x)$

$a_4 = \frac{1}{x} - 3 + 2x$

$a_5 = \beta\ (2 - \frac{1}{x} - x)$

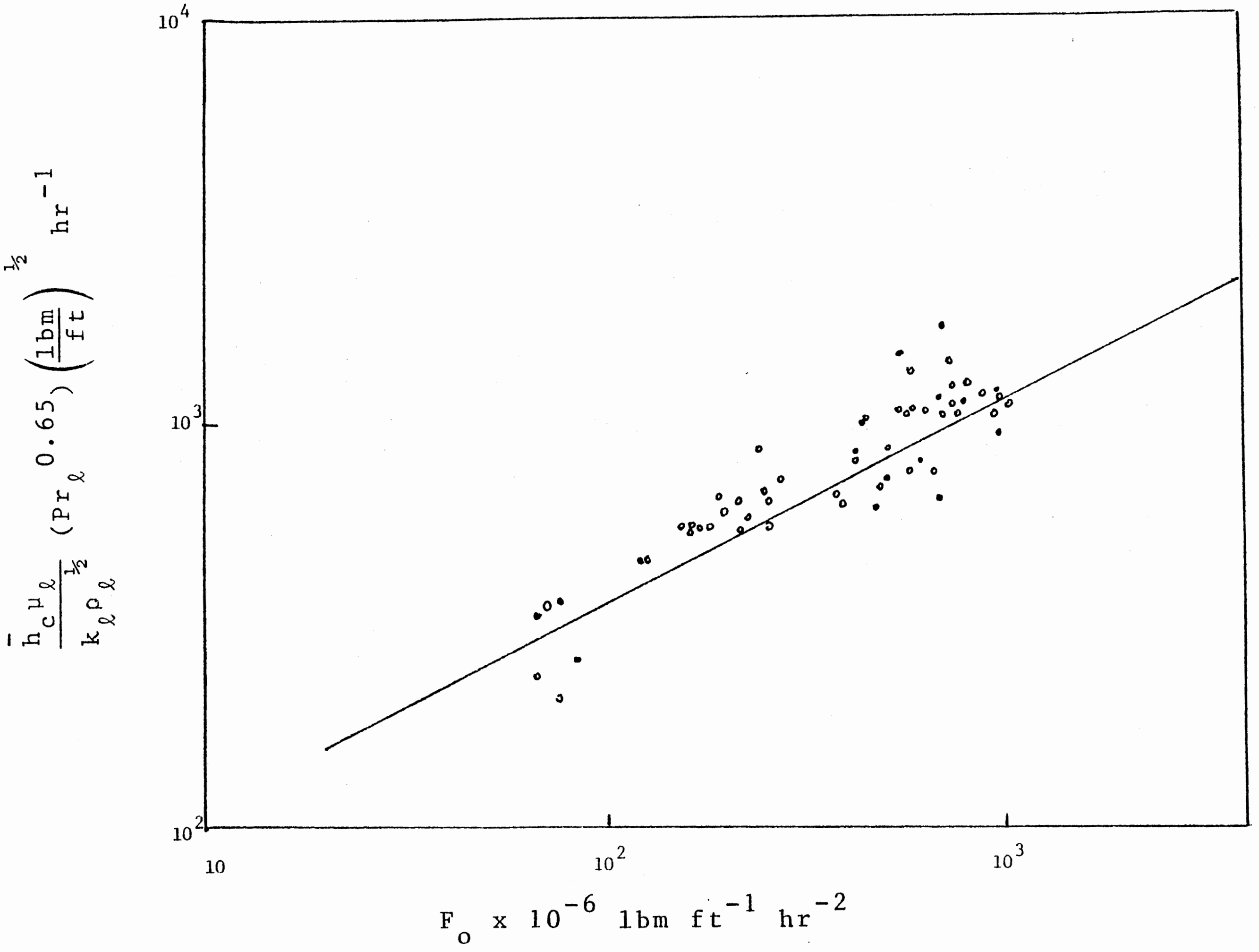


Figure 10. Local Heat Transfer Data for Condensation Inside Tube (Line represents Equation 2.14). (14)

x is the quality and β is the ratio of mean liquid film velocity to the interfacial velocity.

$$V_{\ell_i} = \beta V_{\ell} \tag{2.22}$$

where V_{ℓ} (average liquid velocity) is:

$$V_{\ell} = \frac{(1 - x)\, W_t}{\rho_{\ell}\,(1 - \alpha)\, A} \tag{2.23}$$

and α, the void fraction as proposed by Zivi is:

$$\alpha = \frac{1}{1 + \left(\frac{1 - x}{x}\right)\left(\frac{\rho_v}{\rho_{\ell}}\right)^{2/3}} \tag{2.24}$$

The effect of the gravitational field on the shear stress F_a is given by:

$$F_a = \frac{D}{4}\,(1 - \alpha)\,(\rho_{\ell} - \rho_v) g \operatorname{Sin} \theta \tag{2.25}$$

Soliman, et al., analysis also presents a means of predicting the onset of liquid runback in the presence of an adverse gravitational field.

Equations 2.17 through 2.25 are also valid for the case of upward vapor flow. In the force balance, the gravity term will, however, be negative.

$$F_o = F_f + F_m - F_a \tag{2.26}$$

The gravity contribution F_a, although quite negligible at high quality for vertical downflow, is very significant for the case of upward flow. In fact, to avoid flooding of tubes, the gravity term should dominate.

As pointed out earlier, to avoid plugging and slugging of tubes in a reflux condenser, the vapor velocity must be below a critical value. English, et al., (2) conducted an experimental study to determine the effect of various factors on the flooding point. A plot of pressure drop versus the vapor mass flow rate defines the flooding point adequately (Figure 11).

As the gas rate increases, pressure drop increases slowly and when the loading begins, there is a sharp rise and then the second break point in Figure (11) denotes the flooding point.

Based on 56 flooding determinations, English et al. (2) gave the following equation for flooding velocity:

$$G = 1550\ D^{0.3}\ \rho_\ell^{0.46}\ \sigma^{0.9}\left(\rho_v^{0.5}/\mu_\ell^{0.14}\right)(\text{Cos}\ \theta)^{.32}\left(\frac{L}{G}\right)^{0.07} \qquad (2.27)$$

where G - Maximum allowable vapor mass velocity, lb/hr sq ft.

D - Inside diameter of tube, inches

ρ_ℓ, ρ_v - Liquid and vapor density respectively, lb/cu ft

μ_ℓ - Liquid viscosity, centipoise

α - Surface tension, dynes/cm

θ - Tube taper angle, degrees

Equation (2.26) is shown graphically in Figure 12. All factors such as gas and liquid rates, physical properties, tube diameter and the angle of taper on the tube inlet were taken into account experimentally.

Later, Diehl and Koppany (16) developed a correlation to predict the vapor flooding velocity for vapor-liquid counterflow in vertical tubes. A broad range of physical properties and tube sizes was covered in their experiments and the correlation was tested for a wide range of operating conditions including the English et al. data. The correlation is:

$$V_f = F_1 F_2 \left(\frac{\sigma}{\rho_v}\right)^{0.5} \quad \text{for} \quad F_1 F_2 \left(\frac{\sigma}{\rho_v}\right)^{0.5} > 10 \qquad (2.28)$$

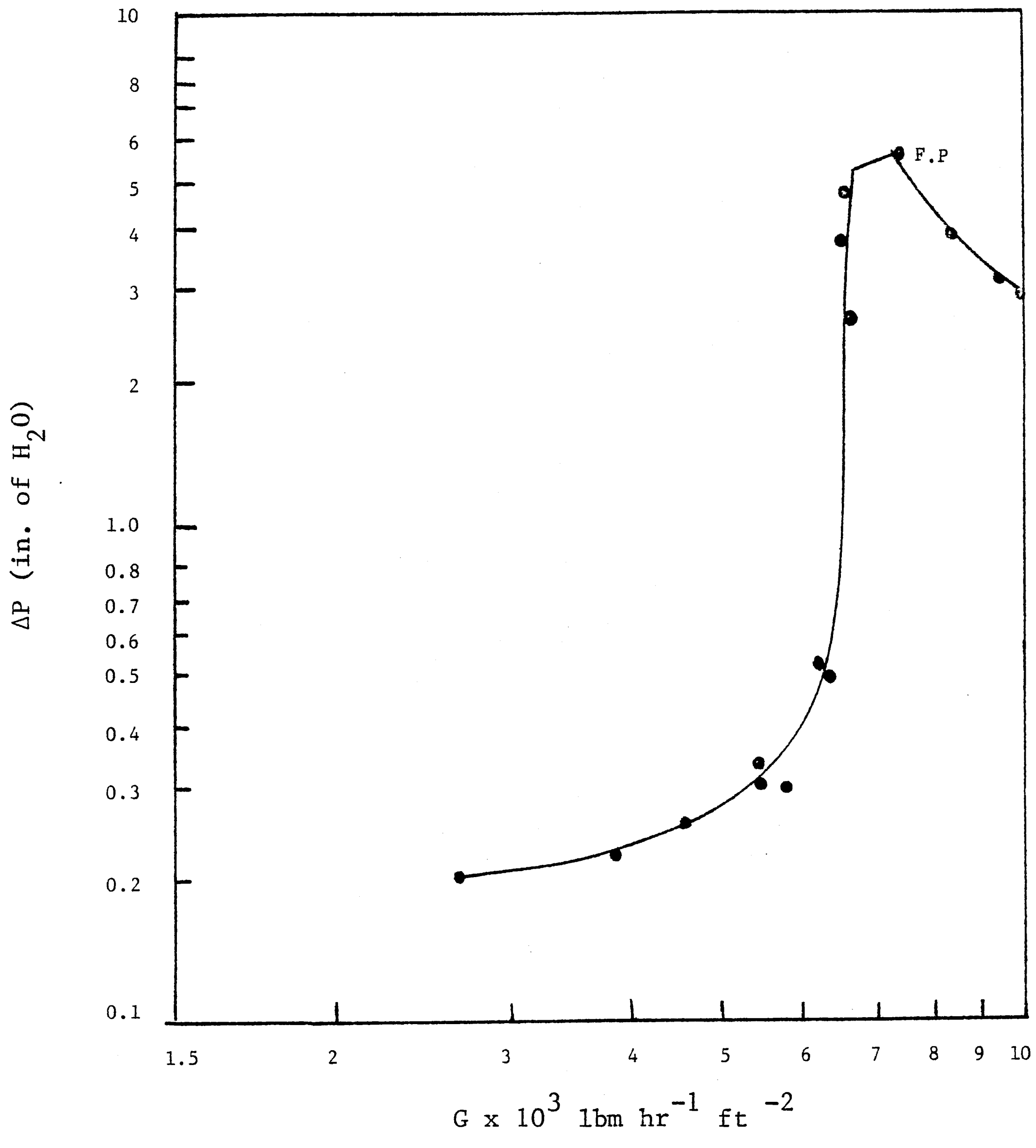


Figure 11. Pressure Drop versus Gas Mass Velocity (n-Propyl Alcohol with 75° Diagonally-cut Tube End).

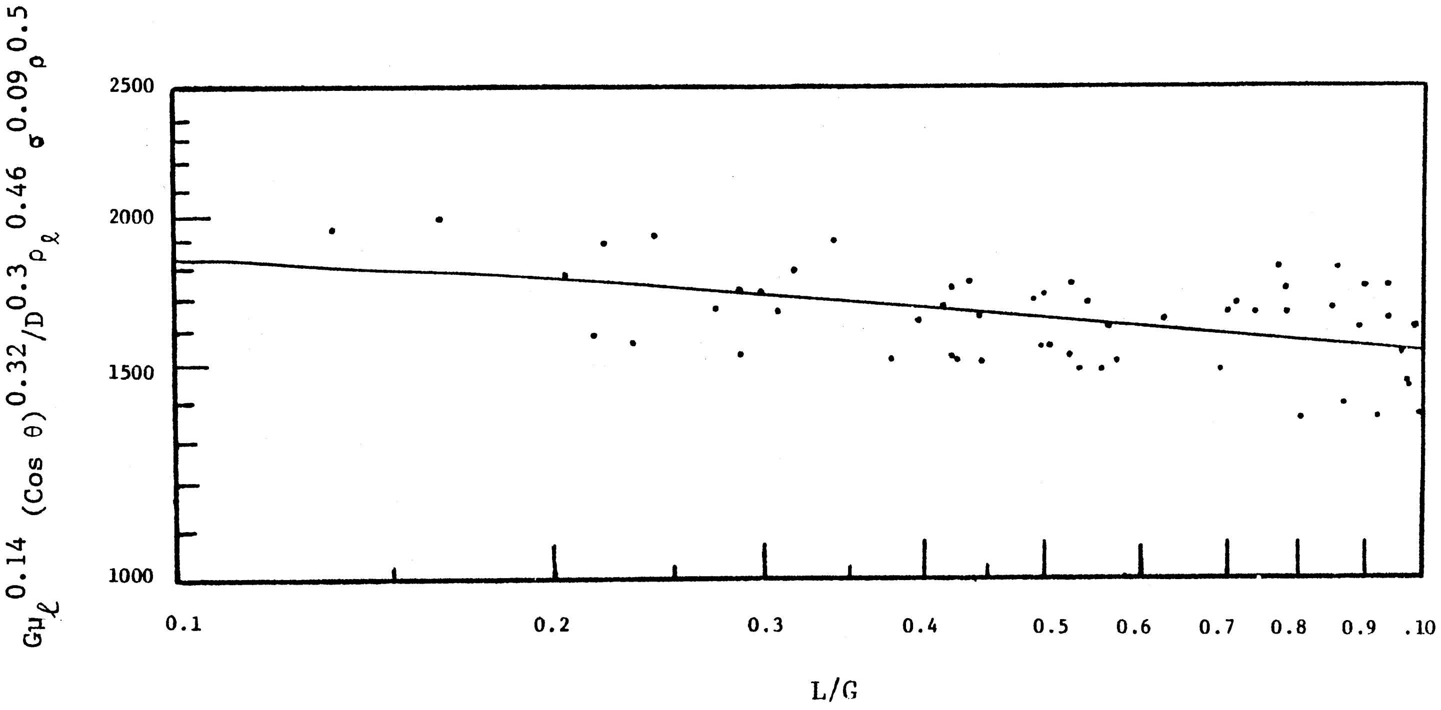


Figure 12. Flooding Correlation Based on 56 Flooding Determinations. (1)

$$V_f = 0.71 \left[F_1F_2 \left(\frac{\sigma}{\rho_v}\right)^{0.5} \right]^{1.15} \quad \text{for } F_1F_2 \left(\frac{\sigma}{\rho_v}\right)^{0.5} < 10 \tag{2.29}$$

where;

$$F_1 = \left[d_i/\left(\frac{\sigma}{80}\right) \right]^{0.4} \tag{2.30}$$

$$F_1 = 1.0 \text{ if } di/(\sigma/80) \geq 1.0 \tag{2.31}$$

$$F_2 = \left(\frac{L}{G}\right)^{0.25} \tag{2.32}$$

Since the equations are dimensional, the units to be used are:

σ - dynes/cm

d_i - inches

ρ_v, ρ_ℓ - lbm/ft^3

L,G - lbm/hr ft^2

and V_f is in ft/sec.

The above equations can be represented by a graph (Figure 13).

The case of binary and multicomponent vapor condensation in a knockback condenser has not yet been fully explored. This is because of complications due to mass transport in addition to flooding possibilities. The basic equations for handling binary mixtures were first formulated by Colburn and Drew (17) and have recently been programmed by Price and Bell (18).

For multicomponent vapor condensation, a rigorous analysis is still under development. Only an approximate design procedure is available. It was first proposed by Silver (19) and later modified by Ward (20). Ward's analysis, however, neglects sensible heat of cooling the condensate and the transport of this heat through the condensate film. Bell and Ghaly (3) modified Ward's analysis to account for the above shortcoming.

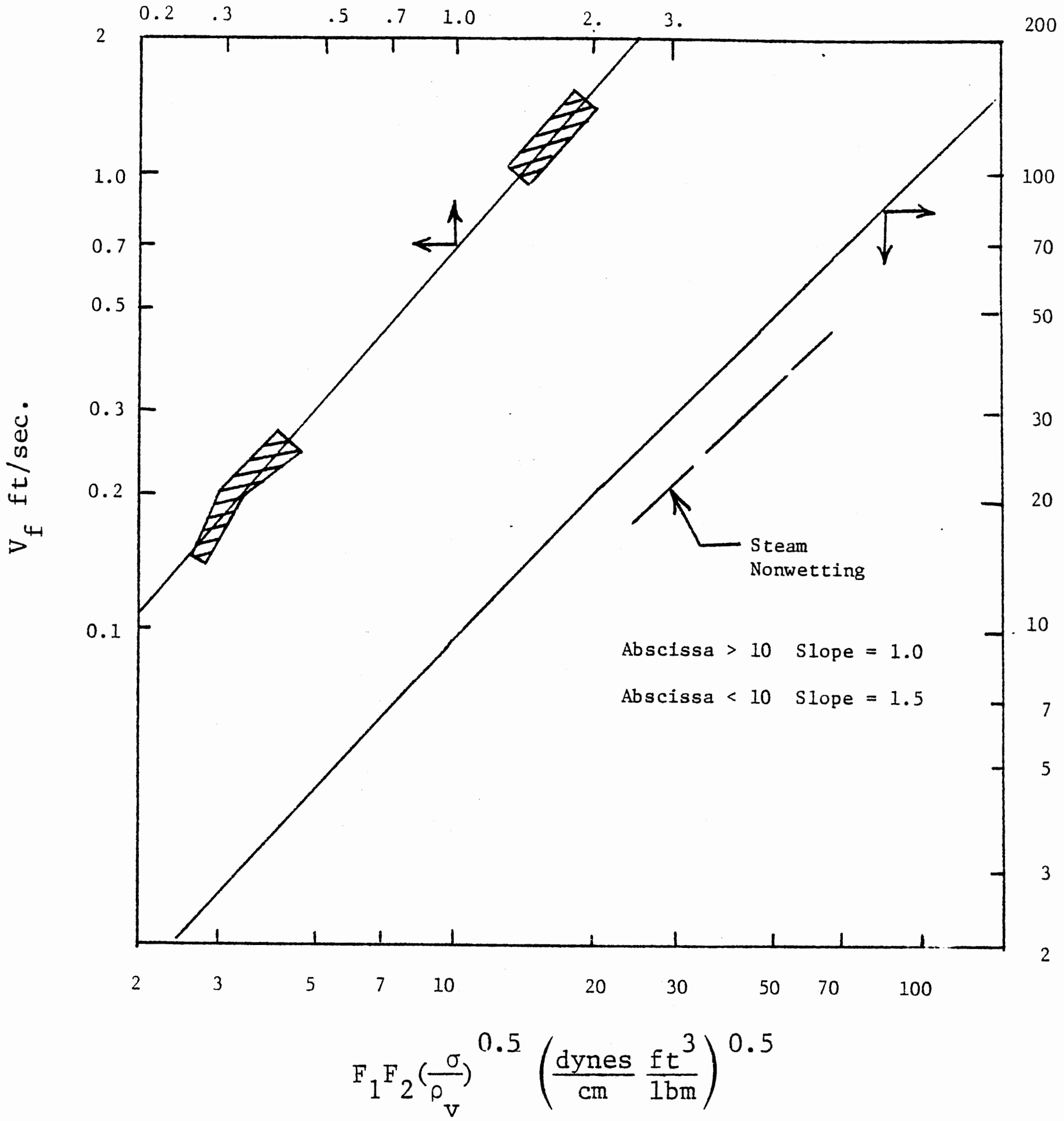


Figure 13. Flooding Velocity Correlation for Gas-Liquid Countercurrent Flow in Vertical Tubes. (16)

The main assumption made in this type of anlysis is that the mass transfer resistance in the vapor phase can be replaced by a conservative estimate of the heat transfer resistance in the vapor. The present analysis assumes the validity of this approach for a knockback condenser. The condensate heat transfer coefficient is estimated by the modified Carpenter and Colburn equations as suggested by Soliman et al. (14). Due to vapor shear the condensate layer becomes turbulent at much lower values of Reynolds number than in the absence of vapor shear. The transition Reynolds number was found to be equal to 240 (7). At lower Reynolds number, the condensate heat transfer coefficient is estimated by both Nusselt's equation and Colburn's equation. The higher value is chosen for design purposes. In the presence of vapor shear, Soluman et al. found by experiments the value of $b_1 = 0.036$ where

$$b_1 \mathrm{Pr}_\ell{}^C = \frac{h_c(z)\ \mu_\ell}{k_\ell \rho_\ell{}^{\frac{1}{2}} F_o{}^{\frac{1}{2}}} \tag{2.33}$$

and $C = 0.65$

In the equation presented by Carpenter and Colburn (7), b_1 was equal to 0.045 and C equal to F. Carpenter and Colburn assumed that the interfacial shear stress was equal to wall shear stress and hence the difference in the values of b_1 and C.

CHAPTER III

FILM FLOW MODEL AND HEAT TRANSFER MODEL

Pure Component Condensation

The basic design equation used here are those developed by Soliman et al. (14). The stress acting downwards is taken as positive. Since in the case of upward vapor flow, gravity opposes the vapor shear at the vapor-liquid interface, the friction term is negative.

As mentioned earlier, the main concern in reflux condensers is that flooding be avoided, i.e., the sum of the three terms (friction, gravity and momentum) should not be equal to zero, i.e.,

$$F_o = F_a + F_m - F_f > 0 \tag{3.1}$$

For a fixed tube diameter, the flooding velocity depends on the vapor density and liquid surface tension (16). In very small diameter tubes, countercurrent flow is not possible due to surface tension effects.

Diehl and Koppany (16) found that there is a definite critical diameter, above which the flooding velocity is no longer dependent on the choice of the diameter. This critical diameter is dimensional;

$$D_c = \frac{\sigma}{80} \tag{3.2}$$

where σ is in dynes/cm and D_c is in inches.

The final form of the flooding correlation is the set of equations 2.28 through 2.32 The recommended operating velocity is about 70 percent of the flooding vapor velocity. The main assumptions governing the analysis of Soliman et al. are:

a. Annular flow is assumed throughout the condensing length (Figure 14).

b. In the presence of vapor shear, transition from laminar to turbulent flow occurs at a Reynolds number, $\frac{4W_\ell}{\pi D\mu_\ell}$, of about 250.

c. There is zero slip at the vapor-liquid interface.

d. Carpenter-Colburn type heat transfer coefficient (with vapor shear effect) is applicable in turbulent flow regime and Nusselt equation in laminar flow regime.

The details of development of the various terms in equation 3.1 are given by Soliman et al. (14). The final form of the equations are:

Gravity term

$$\frac{F_a}{\left(\frac{8W_T^2}{\pi^2\rho_v D^4}\right)} = 0.5\,F_{rt}^{-1}\left[1-\left\{1+\frac{(1-x)}{x}\left(\frac{\rho_v}{\rho_\ell}\right)^{2/3}\right\}^{-1}\right] \qquad (3.5)$$

$$\text{where } F_{rt} = \frac{16\,W_T^2}{\pi^2 D^5 g(\rho_\ell-\rho_v)\rho_v} \qquad (3.4)$$

Friction term

$$\frac{F_f}{\frac{8W_T^2}{\pi^2\rho_v D^4}} = 0.045\,Re_T^{-0.2}\left[x^{1.8}+5.7\left(\frac{\mu_\ell}{\mu_v}\right)^{0.0523}(1-x)^{0.47}\,x^{1.33}\left(\frac{\rho_v}{\rho_\ell}\right)^{0.261}+8.11\left(\frac{\mu_\ell}{\mu_v}\right)^{0.105}(1-x)^{0.94}\,x^{0.86}\left(\frac{\rho_v}{\rho_\ell}\right)^{0.522}\right] \qquad (3.5)$$

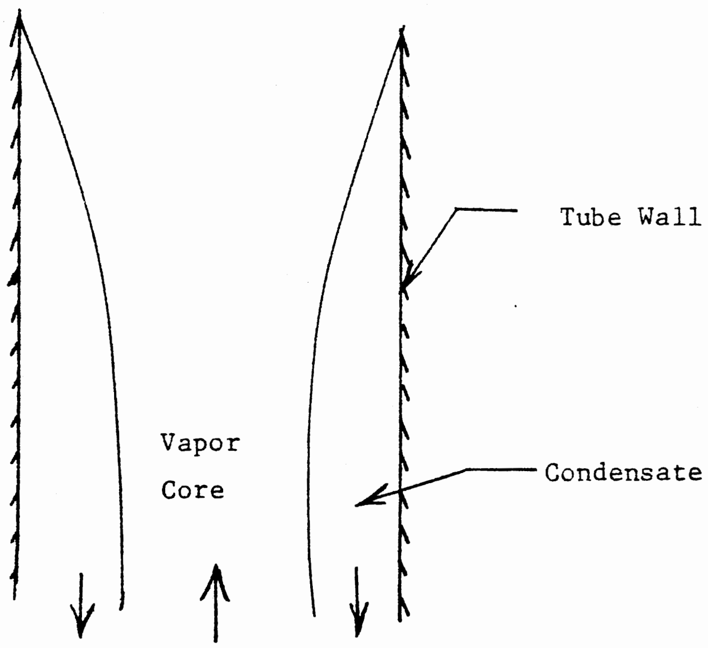


Figure [redacted] Annular Film Flow.

where $Re_T = \frac{4W_T}{\pi D \mu_v}$ (3.6)

and finally,

$$\frac{F_m}{\left(\frac{8W_T^2}{\pi^2 \rho_v D^4}\right)} = 0.5 \left(D \frac{\Delta x}{\Delta z}\right) \left[2(1-x) \left(\frac{\rho_v}{\rho_\ell}\right)^{2/3} + \left(\frac{1}{x} - 3 + 2x\right) \left(\frac{\rho_v}{\rho_\ell}\right)^{4/3}\right.$$

$$+ (2x - 1 - \beta x) \left(\frac{\rho_v}{\rho_\ell}\right)^{1/3} + \left(2\beta - \frac{\beta}{x} - \beta x\right) \left(\frac{\rho_v}{\rho_\ell}\right)^{5/3}$$

$$\left. + 2(1 - x - \beta + \beta x) \left(\frac{\rho_v}{\rho_\ell}\right)\right] \qquad (3.7)$$

where β is the ratio of the interfacial velocity to the average liquid layer velocity. In the present case, the sum of the above three effects gives the shear stress at the tube wall.

$$F_o = F_a + F_m - F_f$$

It should be noted that the left-hand sides of equations 3.3, 3.5 and 3.7 are dimensionless and they will be denoted as F_a', F_f' and F_m'.

Evaluation of Local Heat Transfer Coefficient

On the basis of experimental results, Carpenter and Colburn (17) arrived at the following equation for local condensate heat transfer coefficient:

$$\frac{h_c(z)\,\mu_\ell}{k_\ell\,\rho_\ell^{1/2}} = 0.043\,(Pr_\ell)^{1/2}\,F_o^{1/2} \qquad (3.8)$$

However, Soliman et al. (14) found the coefficient of 0.043 and the Prandtl number of exponent of 0.5 unsatisfactory over a wide range of Prandtl numbers. Based on their experiments, Soliman et al. (14)

found that a coefficient of 0.036 and an exponent 0.65 more satisfactory. The modified equation is then:

$$\frac{h_c(z)\ \mu_\ell}{k_\ell\ \rho_\ell^{1/2}} = 0.036\ \mathrm{Pr}_\ell^{\ 0.65}\ F_o^{\ 1/2} \tag{3.9}$$

Figures 10 and 15 show how from the data these two constants are determined.

Mass and Energy Balance for Pure Component Condensation

In the present analysis, only a saturated vapor feed has been considered; i.e.,

$$Q_T = W_T \lambda$$

This however, can be modified if required to handle superheated vapor. An additional heat balance to desuperheat the feed will be required. All calculations are carried out for a single tube. If the total heat duty is specified, then the total number of tubes required may be obtained by dividing the total heat duty by the heat transferred per tube.

First the flooding velocity of the vapor is computed by the Diehl and Koppany correlation. Then the inlet velocity is taken as 70 percent of the flooding velocity (Figure 16). If only a fraction of the vapor is condensed then;

$$W_{v,\ out} = W_{v,\ in}\ (FC)$$

where FC is the fraction condensed.

$$Q_T/\text{tube} = W_v \lambda \tag{3.10}$$

$$W_{cool}/\text{tube} = \frac{Q_T/\text{tube}}{C_{p,cool}(T_2 - T_1)} \tag{3.11}$$

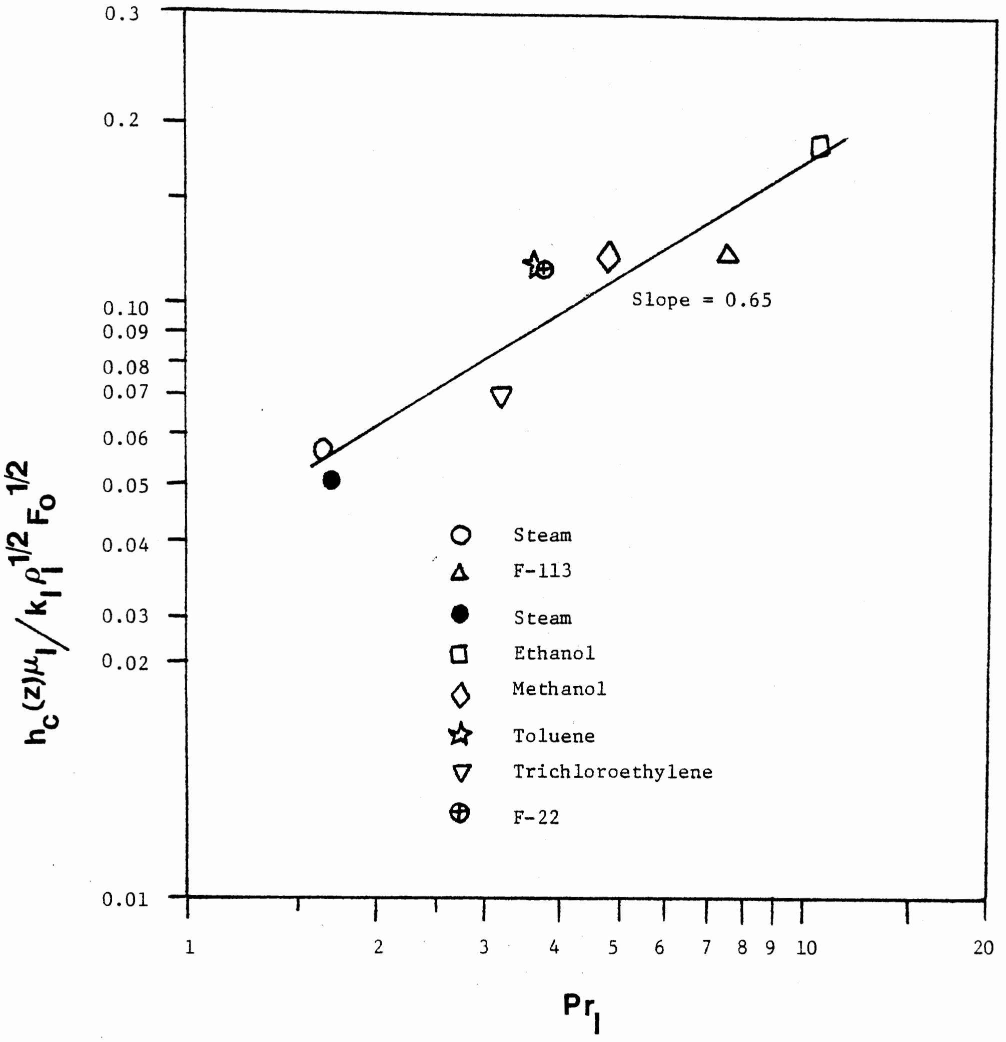


Figure 15. Evaluation of Prandtl Number Exponent in Equation 2.14. (14)

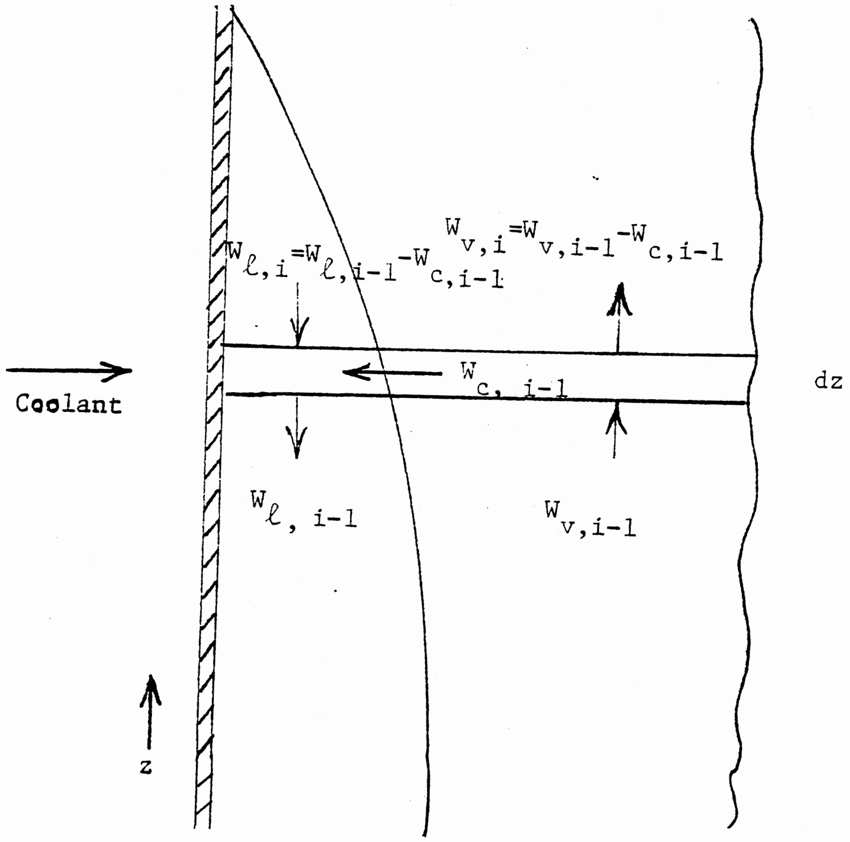


Figure 16. Mass Balance for Pure Component Condensation.

where T_1 and T_2 are the inlet and outlet coolant temperatures respectively. The computational procedure for pure component condensation is as follows:

1. Assume length of tube (L_T)
2. Startup at $z = 0$, calculate $h_c(z)$, i, and $U'_{i,\,i}$ where U_i' is the overall heat transfer coefficient

$$U_i' = \frac{1}{\frac{1}{h_c(z)} + R_{fi} + \frac{\Delta x_w}{k_w}\left(\frac{D}{OD}\right) + R_{fo}\,\frac{D}{OD} + \frac{1}{h_{cool}}\,\frac{D}{OD}} \qquad (3.12)$$

where R_{fi}, R_{fo} are the inside and outside fouling factors, respectively, and

Δx_w wall thickness

OD outer diameter of tube

3. Choose a very small increment Δz. Assuming that the values computed at i hold good over the increment Δz,

$$T_{w,\,i+1} = T_{sat} - \left(\frac{U_i'}{h_c(z)}\right)(T_{sat} - T_{i,i}) \qquad (3.13)$$

The incremental heat recovery is

$$\Delta Q_{i+1} = \pi D \Delta z U'_{i,\,i}\,(T_{sat} - T_i) \qquad (3.14)$$

The amount of vapor condensed is given by

$$W_{c'i+1} = \Delta Q_{i+1}/\lambda \qquad (3.16)$$

The mass flow rates of vapor and liquid are:

$$W_{v,i+1} = W_{v,i} - W_{c,i+1} \quad \text{and} \qquad (3.16a)$$

$$W_{\ell,i+1} = W_{\ell,i} - W_{c,i+1} \qquad (3.16b)$$

The total mass flow rate at (i + 1) iteration is

$$W_{\ell, i+1} + W_{v, i+1} \quad (3.16c)$$

and quality

$$X_{i+1} = W_{v, i+1}/W_{T, i+1} \quad (3.17)$$

4. Calculate $h_c(z)_{, i+1}$ and $V_{i, i+1}$

5. The coolant temperature is

$$T_{i+1} = T_i \pm \Delta Q_{i+1}/C_{p, cool} W_{cool} \quad (3.18)$$

where the positive sign should be used if the coolant and the vapor are cocurrent and the negative sign if the coolant and the vapor are in counter current flow (Figure 17b)

Check if $ABS\left|Q_T - Q_{i+1}\right| \le \varepsilon$

where ε is a very small number and then check if $(\Sigma z - L_T) \le \varepsilon$

No, go on to step 3.

Yes, the length of the tube has converged.

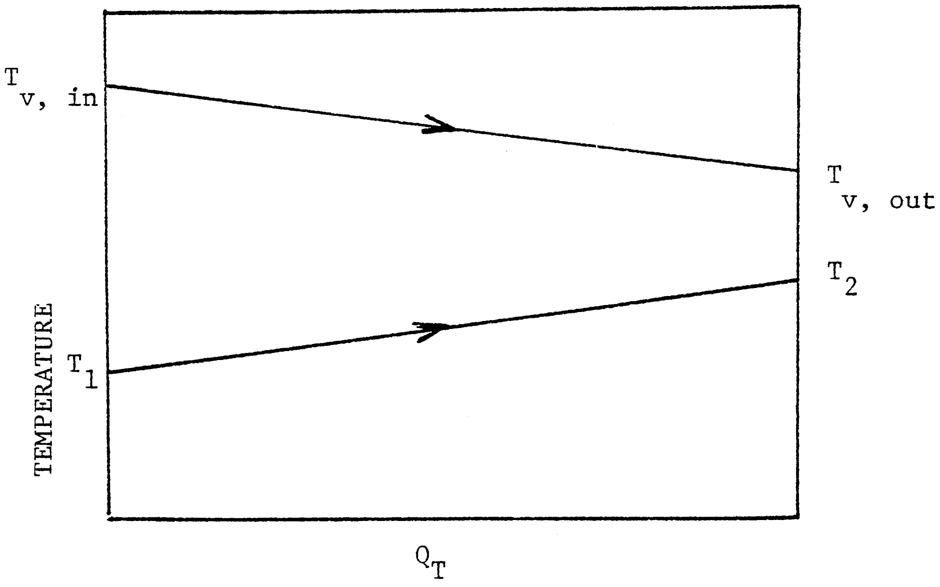
Multicomponent Condensation

As mentioned earlier, no rigorous method is available at present to handle multocomponent condensation. This is because of the mass transport involved. The approximate design procedure as presented by Bell and Ghaly (3) will be used in the analysis.

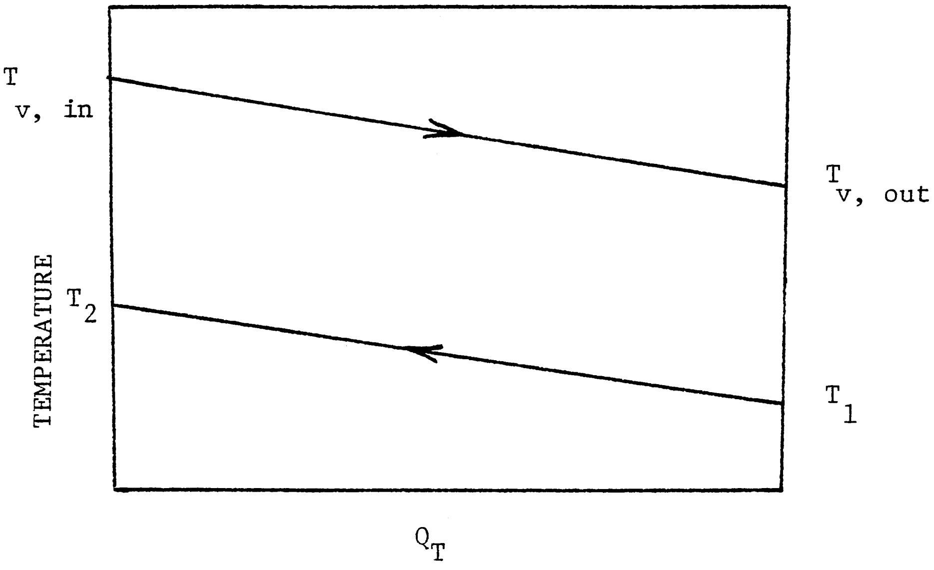
The basic assumptions in this method are:

1. The liquid and vapor composition are in equilibrium at the vapor bulk temperature.

2. Liquid and vapor enthalpies are those of the equilibrium phases at the vapor bulk temperature.



a) Cocurrent Flow



b) Countercurrent Flow

Figure 17. Flow Configuration for Vapor and Coolant

3. The sensible heat of the vapor is transferred from the bulk vapor to the vapor liquid interface by a convective heat transfer process. The heat transfer coefficient is calculated from a correlation for the geometry involved, assuming that only the vapor phase is present and using vapor physical properties and total vapor flow rate.

4. Total latent heat of condensation and sensible heat of the cooling condensate are transferred through the entire thickness of the liquid Film.

Figure 18 shows typical multicomponent condensation profiles for a system consisting of two condensable components and one noncondensable. Figure 19 shows the idealized model for a multicomponent condensation.

By heat balance,

$$\frac{dQ_{sv}}{dA_i} = h_{sv}\,(T_v - T_i) \tag{3.19}$$

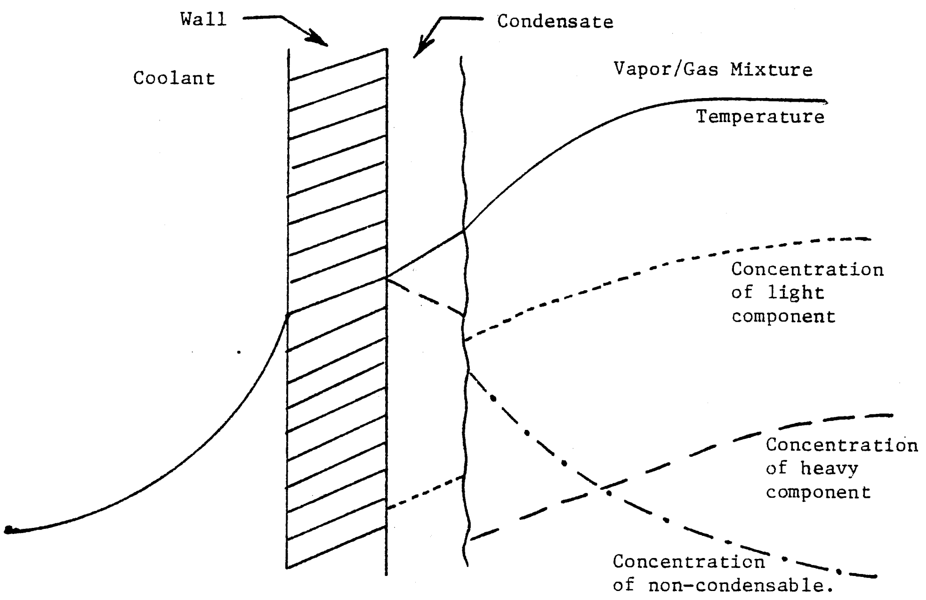
$$\frac{dQ_T}{dA_i} = U_i'\,(T_i - T_{cool}) \tag{3.20}$$

Eliminating T_i between equations results in a form that can be readily used in the design.

$$\frac{dQ_T}{dA} = \frac{U_i'\,(T_v - T_{cool})}{1 + \frac{ZU_i'}{h_{sv}}} \tag{3.21}$$

where

$$Z = \frac{dQ_{sv}}{dQ_T} \tag{3.22}$$



✓Figure 18. Multicomponent Condensation Profile. (18)

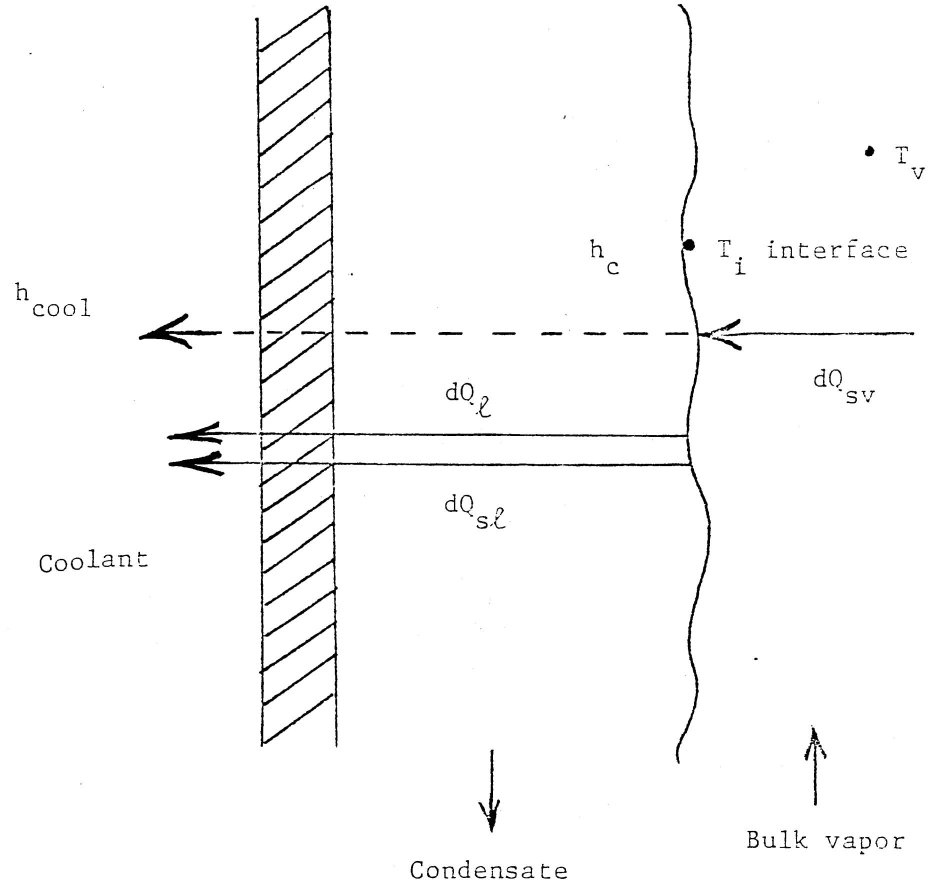


Figure 19. Idealized Model for Multicomponent Condensation. (3)

The single phase vapor sensible heat transfer coefficients h_{sv}, was calculated using the Seider-Tate equation

$$h_{sv} = 0.23\left(\frac{k_v}{D}\right)\left(\frac{C_p\mu}{k}\right)_v^{0.33}\left(\frac{D\,W_v}{\left(\frac{\pi}{4}D\right)^2\mu_v}\right)^{0.8}\left(\frac{\mu}{\mu_s}\right)_v^{0.14} \qquad (3.23)$$

where W_v varies for every finite increment.

Mass and Energy Balance for Multicomponent Condensation

As in the case of pure component condensation, the flooding vapor velocity is first estimated using the Diehl and Koppany correlations. The operating vapor flow rate is then calculated as:

$$W_v = 0.7V_f\left(\frac{\pi D^2}{4.0}\right)\rho_v \qquad (3.24)$$

The average value of the vapor mixture density can be used if the properties do not vary much over the range of temperatures.

Since the inlet vapor mixture flow rate, temperature, pressure and composition of the vapor mixture will generally be specified, it is possible to calculate the intermediate liquid and vapor flow rates and the compositions by equilibrium calculations. If the fraction condensed is specified, the outlet temperature can be obtained or vice versa.

In the present analysis, all these parameters were obtained by using the GPA*SIM program (4)..

Here, at a given temperature and pressure, a value of L/F is assumed and the k_i values for each component are taken at the pressure and temperature specified.

If $\frac{L}{F}$ assumed is the same as $\frac{L}{F}$ calculated

(Actually Abs $\frac{L}{F}_{\text{assumed}} - \frac{L}{F}_{\text{calculated}} \leq 0.0005$)

then the composition at the required temperature and pressure is obtained.

Calculation of $\frac{L}{F}$

1. Assume $\frac{L}{F}$

2. $$\phi(\tfrac{L}{F}) = \frac{\Sigma M_i(1 - k_i)}{\frac{L}{F}(1 - k_i) + k_i} \qquad (3.25)$$

3. $$\phi'(\tfrac{L}{F}) = \frac{-\Sigma M_i(1 - k_i)^2}{\left[\frac{L}{F}(1 - k_i) + k_i\right]^2} \qquad (3.26)$$

4. $$\frac{L}{F}\bigg|_{\text{new}} = \frac{L}{F}\bigg|_{\text{old}} - \frac{\phi(L/F)}{\phi'(L/F)} \qquad (3.27)$$

5. $$\text{If ABS } \left|(\tfrac{L}{F})_{\text{new}} - (\tfrac{L}{F})_{\text{old}}\right| \leq 0.0005 \qquad (3.28)$$

   Yes - Go to 6

   No - Go to 1

6. $$x_i = \frac{M_i}{\frac{L}{F}(1 - k_i) + k_i} \; ; \; y_i = k_i x_i$$

Similar calculations can be done for the condensing range of the vapor to the condenser, choosing small increments of ΔT.

Since the ratio of vapor to liquid is known at various points in the condenser as a function of Q the liquid and the vapor flow rates can be readily calculated (Figure 20).

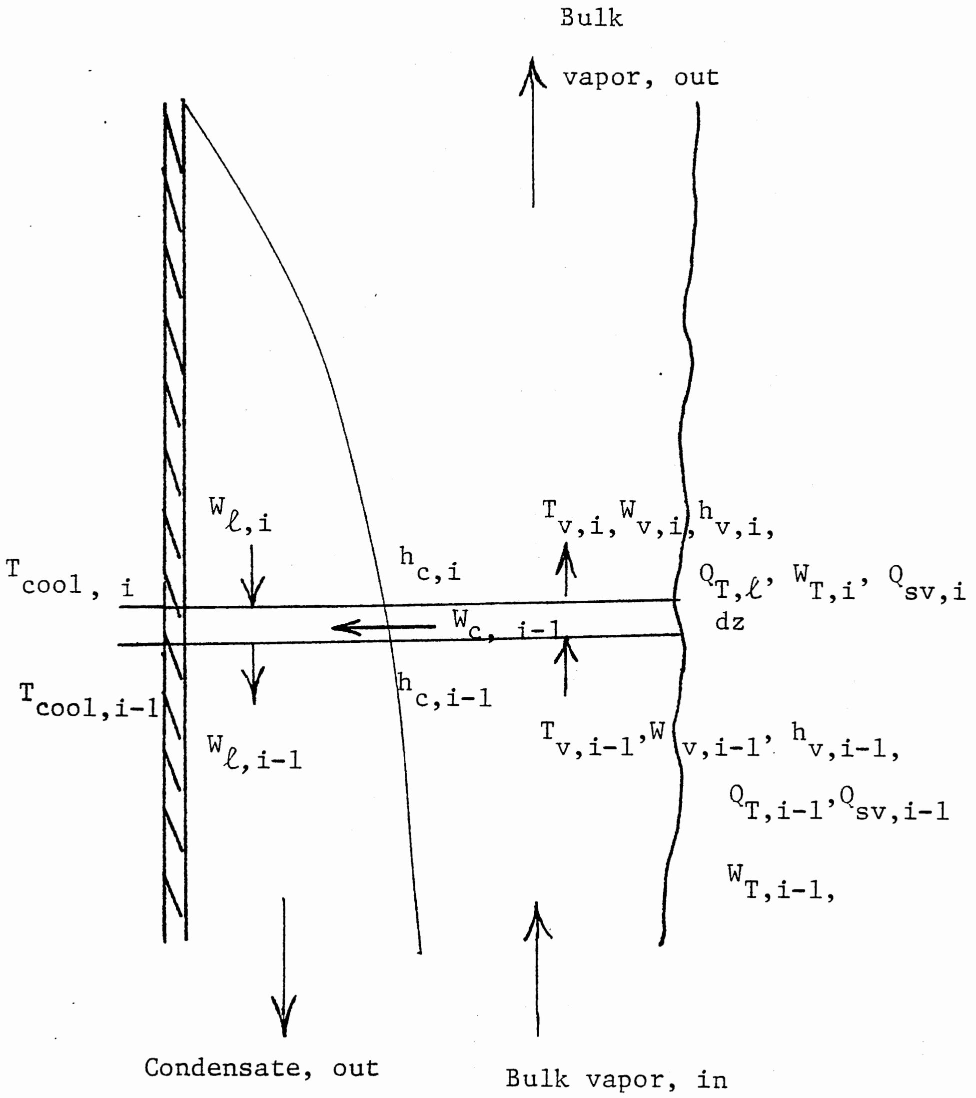


Figure 20. Mass and Energy Balance for Multicomponent Condensation.

In order to calculate the heat recovered in each increment

$$\frac{dQ_T}{dA_i} = \frac{U'_{i,\ i}\,(T_{v,\ i} - T_{cool,\ i})}{1 + \dfrac{Z_i\ U'_{i,\ i}}{h_{sv,\ i}}} \tag{3.29}$$

where $T_{v,\ i}$ is the bulk vapor temperature

and $$\frac{dQ_T}{dA_i} = \frac{dQ_{sv} + dQ_{s\ell} + dQ_{\ell}}{dA_i} \tag{3.30}$$

GPA*SIM (4) program was used to obtain the enthalpy of vapor and total enthalpy at each increment. The stepwise calculation procedure is as follows:

1. Using GPA*SIM program, precalculate the condensation curve, i.e., the vapor, liquid and total flow rates at various increments of ΔT.

2. Assume length of tube (L_T)

3. At z = 0, calculate $h_c(z)_{,\ i}$, $U'_{i,\ i}$ and $h_{sv,\ i}$

$$\begin{aligned} \text{Set } \Delta Q_{sv,\ i} &= 0 \\ \Delta Q_{T,\ i} &= 0 \\ h_{sav,\ i} &= 0 \\ Z_i &= 0 \\ Q_{y,\ i} &= 0 \end{aligned}$$

where $Q_{y,\ i}$ is the total heat recovered up to increment in question starting from z = 0.

4. Increment $z_{i + 1} = \Delta z$ (over which the bulk vapor temperature goes from $T_{v,\ i}$ to $T_{v,\ i + 1}$)

5. Calculate the differential vapor sensible load as

$$\Delta Q_{sv,\ i + 1} \overset{=}{\cancel{*}} \left[(W_{v,\ i + 1} + W_{v,\ i})\ /2.0 \quad (h_{v,\ i} - h_{v,\ i + 1}) \right] \tag{3.31}$$

where h_v is the vapor enthalpy.

6. $$Q_{y,\ i+1} = W_{v,\ inlet}\,(h_{T,\ i+1} - h_{T,\ i+1}) \tag{3.32}$$

and the differential heat recovered is

$$\Delta Q_{T,\ i+1} = Q_{y,\ i+1} - Q_{y,\ i} \tag{3.33}$$

7. The collant temperature is

$$T_{i+1} = T_c \pm \Delta Q_{T,\ i+1}/C_{p,\ cool}\,W_{cool} \tag{3.34}$$

8. $$Z_{i+1} = \Delta Q_{sv,\ i+1}/\Delta Q_{T,\ i+1} \tag{3.35}$$

9. $$H_{svav,\ i+1} = (h_{sv,\ i+1} + h_{sv,\ i})/2.0 \tag{3.36}$$

10. Calculate the condensation heat transfer coefficient,

$h_c(z)_{,\ i+1}$, and $U'_{i,\ i+1}$

11. $$\text{Factor}_{,\ i+1} = \frac{\dfrac{1 + Z_{i+1}\,U'_{i+1}}{h_{svav,\ i+1}}}{U'_{i,\ i+1}\,(T_{v,\ i+1} - T_{i+1})} \tag{3.37}$$

12. Calculated increment is

$$\Delta z_{cal} = \frac{(\text{Factor}_{\ i+1})\,\Delta Q_{T,\ i+1}}{\pi D} \tag{3.38}$$

check if $\text{Abs}|\Delta z, \text{assumed} - \Delta z,_{cal}| \leq \varepsilon$

Yes, repeat for the next ΔT increment and go to step 4.

No, choose another Δz and go to step 10.

13. At the end of all ΔT increments, check if $(\Sigma\Delta z - L_T) \leq \varepsilon$.

Yes, length of the tube has converged.

No, assume a new L_T and go to step 2.

The length of the tubes then $\sum_i \Delta z_i$. Alternatively, a plot of

$$\frac{1 + \dfrac{zU'_i}{h_{sv}}}{U'_i(T_v - T_{cool})} \qquad \text{versus } Q_T$$

can be drawn and the area under the curve will give the area of the tube (πDL_T) from which the length can be computed. In this case also, calculations were done for a single tube. The number of tubes required can be calculated

$$N_{Tubes} = \frac{\text{Total mass flow rate}}{\text{Mass flow rate per tube}} \tag{3.39}$$

The details of the shell-side design are not present in this analysis. As mentioned earlier, the coolant side coefficient was assumed in the example calculations.

CHAPTER IV

RESULTS AND DISCUSSION

A computer program has been written to handle pure component as well as multicomponent condensation. The program computes the flooding velocity in the reflux condenser. Then, based on the maximum allowable design vapor inlet velocity, point values of the condensate heat transfer coefficients, overall heat transfer coefficients and heat load are calculated. The length of tube is determined by trial and error procedure. For a given total heat load, the number of tubes required is evaluated.

Since the operating vapor velocity was taken to be below the flooding velocity (70 percent flooding velocity) of the vapor, a downward flow of the condensate is ensured. This can be seen in Figures 21 and 24. The gravity term should dominate to prevent flooding in the tubes. If the inlet velocity of the vapor is high enough to cause flooding in the tubes, the condensate will cease to flow down the tube walls. Once the sum of the three effects (momentum, gravity and friction) equals zero, the liquid will slowly start to flow upwards and the flow becomes highly unstable. If the velocity is maintained above flooding, there will be a point when the condensate will be carried out of the tube. Hence, the inlet vapor rate into a reflux condenser is the critical design parameter.

As can be seen from the results of examples in Appendix A, the flooding velocity is surprising very low even for a 1.334 in. inside tube diameter.

For the pure component, the flooding velocity is 6.2 ft/sec and for the multicomponent case, it is about 2.5 ft/sec. However, due to higher vapor density for the latter case, the mass flow rate is higher per tube.

The shortcomings of the model are:

1. The use of modified Carpenter and Colburn equations as presented by Soliman et al. (1) for condensate heat transfer coefficient, including vapor shear effects.

   $$h_c(z) = 0.036 \, \mathrm{Pr}_\ell^{0.65} \, F_o^{0.5} \left(\frac{k\rho}{\mu}\right)_\ell^{0.5}$$

   This equation was obtained as a result of experiments, strictly based on data collected for vertical downward flow of vapor. Hence its accuracy for an upward vapor flow is not known and requires experimental verification.

2. The algorithm for the multicomponent case is only an approximate design method because of the assumptions made. The heat transfer resistance in the vapor is overestimated, neglecting the mass transfer resistance. Until a rigorous method is developed to handle multicomponent mixtures and experimental data are made available for reflux condensers, one cannot comment upon the accuracy of the results obtained. However, the coefficients and length of the tubes look reasonable. For safe operation of the condenser, the area provided should be about 20-25 percent in excess of the area computed.

The momentum term as derived by Soliman et al. goes to zero in the case of total condensation for countercurrent flow. Although the changes in momentum may be negligible (as can be seen from Tables VI and XV in Appendix A) the term should not go to zero. This will however, not alter the results significantly.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This thesis deals with an approximate design procedure for pure component and multicomponent reflux condensers.

The basic mechanism of refluz condensation in a vertical tube is still not fully known. This is due to the flooding possibilities.

A computer program is presented in Appendix C that will give the design parameters, such as flooding velocity, heat recovered per tube, the heat transfer coefficients and the length of the tube for a reflux operation. The result can be obtained in SI units or U. S. customary units.

The program however could be modified to accommodate the prediction of various physical properties, which in this program are read as input data. Also, for multicomponent condensation, the preliminary calculations, such as condensing path and enthalpy predictions are not included in the program. These were done by using GPA*SIM (4) but could be included as a callable routine. Also, the program handles saturated vapors alone. It could be modified to handle superheated vapors as well as vapor mixtures containing non-condensables.

The results have been presented at every increment using point condition equations. In order to avoid unrealistic heat transfer coefficients, the higher of the two (Nusselt and Carpenter-Colburn) was chosen. This applies especially near the top of the tubes where the Nusselt region can be expected, due to decreasing vapor velocity.

The main point of concern is the lack of experimental data to compare the accuracy of the result obtained. Further research is greatly desired to study the effect of high vapor velocities on fluid flow, especially in determining the actual mechanism of the flooding phenomena.

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APPENDIX A

SAMPLE CALCULATIONS

Pure Component Condensation

It is desired to condense saturated methanol vapor at about 60 psig (235 F). Water is available at 85 F and it leaves at 120 F. The inside and outside fouling are assume to be 0.0005 and 0.001 hr ft^2 F/BTU respectively. The coolant heat transfer coefficient is assumed to be 1000 BTU/hr ft^2 F.

Estimate the flooding velocity, the heat recovered per tube, the length of the tube and the number of tubes required to recover 2.5×10^6 BTU/hr. Tubes with outer diameter of 1.5 inches and 14 BWG are to be used.

The following results were obtained from the computer program. The length of the tube was obtained by iterating from the bottom of the tube (length = 0), until the assumed length was equal to the calculated length. The results are given for every increment.

TABLE I

INPUT DATA

Saturation Temperature	235.0	Deg.F
Pressure	60.0	Psig.
Coolant Specific Heat	1.0	BTU/lbm Deg.F
Latent Heat of Condensation	440.0	BTU/lbm.
Liquid Density	46.0	Lbm/cu.ft.
Vapor Density	0.32	Lbm/cu.ft.
Vapor Viscosity	0.032	Lbm/ft hr.
Liquid Viscosity	0.39	Lbm/ft hr.
Surface Tension	13.0	Dynes/cm.
Inlet Coolant Temp. ↑	120.0	Deg.F
Outlet Coolant Temp. ↓	85.0	Deg.F
Liquid Thermal Conductivity	0.11	BTU/hr ft Deg.F
Wall Thermal Conductivity	26.0	BTU/hr ft Deg.F
Inside Fouling	0.0005	Hr sq.ft Deg.F/BTU
Outside Fouling	0.001	Hr sq.ft Deg.F/BTU
Liquid Specific Heat	0.5	BTU/lbm Deg.F
Coolant Heat Transfer Coeff.	1000.0	BTU/hr sq.ft Deg.F
Outside Diameter of Tube	1.5	Inches
Wall Thickness	0.083	Inches

TABLE II

PRELIMINARY CALCULATIONS

Flooding Velocity	6.2	FT/SEC.
Operating Velocity	15519.2	FT/HR.
Cross Sectional Area/Tube	0.097	SQFT
Vapor Condensed/Tube	48.2	LB/HR
Heat Duty/Tube	19000.0	BTU/HR
Coolant Rate	545.0	LB/HR

TABLE III

FLOW RATE CALCULATIONS AT VARIOUS POINTS IN THE CONDENSER TUBE

ITER	BULK VAPOR TEMPERATURE (FAHRENHEIT)	COOLANT TEMPERATURE (FAHRENHEIT)	LENGTH (FEET)	VAPOR RATE (LB/HR)	LIQUID RATE (LB/HR)	CONDENSATE RATE (LB/HR)	TOTAL RATE (LB/HR)
1	235.0000	120.0	0.000	48.20	43.38	0.000	91.58
2	235.0000	119.3	0.050	47.29	42.47	0.906	89.77
3	235.0000	118.5	0.100	46.38	41.56	0.911	87.95
4	235.0000	117.8	0.150	45.47	40.65	0.917	86.11
5	235.0000	117.1	0.200	44.54	39.72	0.923	84.27
6	235.0000	116.3	0.250	43.61	38.79	0.929	82.41
7	235.0000	115.5	0.300	42.68	37.86	0.934	80.54
8	235.0000	114.8	0.350	41.74	36.92	0.940	78.66
9	235.0000	114.0	0.400	40.79	35.97	0.946	76.77
10	235.0000	113.2	0.450	39.84	35.02	0.951	74.87
11	235.0000	112.5	0.500	38.89	34.07	0.957	72.95
12	235.0000	111.7	0.550	37.92	33.10	0.963	71.03
13	235.0000	110.9	0.600	36.96	32.14	0.968	69.09

TABLE III (Continued)

ITER.	BULK VAPOR TEMPERATURE (FAHRENHEIT)	COOLANT TEMPERATURE (FAHRENHEIT)	LENGTH (FEET)	VAPOR RATE (LB/HR)	LIQUID RATE (LB/HR)	CONDENSATE RATE (LB/HR)	TOTAL RATE (LB/HR)
14	235.0000	110.4	0.650	35.98	31.16	0.974	67.14
15	235.0000	109.4	0.700	35.00	30.18	0.979	65.18
16	235.0000	108.6	0.750	34.02	29.20	0.985	63.22
17	235.0000	107.8	0.800	33.03	28.21	0.990	61.23
18	235.0000	106.9	0.850	32.03	27.21	0.996	59.24
19	235.0000	106.2	0.900	31.03	26.21	1.001	57.24
20	235.0000	105.3	0.950	30.02	25.20	1.006	55.23
21	235.0000	104.5	1.000	29.01	24.19	1.001	53.20
22	235.0000	103.7	1.050	28.00	23.18	1.017	51.17
23	235.0000	102.9	1.100	26.97	22.15	1.021	49.13
24	235.0000	102.0	1.150	25.95	21.13	1.026	47.08
25	235.0000	101.2	1.200	24.92	20.10	1.031	45.02
26	235.0000	100.4	1.250	23.89	19.06	1.035	42.95
27	235.0000	99.5	1.300	22.84	18.02	1.039	40.87

TABLE III (Continued)

ITER.	BULK VAPOR TEMPERATURE (FAHRENHEIT)	COOLANT TEMPERATURE (FAHRENHEIT)	LENGTH (FEET)	VAPOR RATE (LB/HR)	LIQUID RATE (LB/HR)	CONDENSATE RATE (LB/HR)	TOTAL RATE (LB/HR)
28	235.0000	98.7	1.350	21.80	16.98	1.043	38.78
29	235.0000	97.9	1.400	20.75	15.93	1.046	36.69
30	235.0000	97.0	1.450	19.71	14.89	1.049	34.59
31	235.0000	96.2	1.500	18.65	13.83	1.052	32.49
32	235.0000	95.3	1.550	17.60	12.78	1.053	30.38
33	235.0000	94.5	1.600	16.55	11.73	1.055	28.27
34	235.0000	93.6	1.650	15.49	10.67	1.055	26.16
35	235.0000	92.8	1.700	14.44	9.62	1.054	24.05
36	235.0000	91.9	1.750	13.39	8.57	1.051	21.95
37	235.0000	91.1	1.800	12.34	7.52	1.046	19.86
38	235.0000	90.2	1.850	11.30	6.48	1.039	17.78
39	235.0000	89.4	1.900	10.24	5.42	1.061	15.66
40	235.0000	88.5	1.950	9.15	4.33	1.094	13.47
41	235.0000	87.6	2.000	8.01	3.19	1.136	11.20

TABLE III (Continued)

ITER.	BULK VAPOR TEMPERATURE (FAHRENHEIT)	COOLANT TEMPERATURE (FAHRENHEIT)	LENGTH (FEET)	VAPOR RATE (LB/HR)	LIQUID RATE (LB/HR)	CONDENSATE RATE (LB/HR)	TOTAL RATE (LB/HR)
42	235.0000	86.6	2.050	6.82	2.00	1.189	8.82
43	235.0000	85.6	2.100	5.56	0.74	1.261	6.30
44	235.0000	84.5	2.150	4.18	0.00	1.380	4.18
45	235.0000	85.2	2.200	5.0	0.2	1.409	5.2
46	235.0000	84.0	2.250	3.3	0.0	1.686	3.3

TABLE IV

HEAT TRANSFER CALCULATIONS AT VARIOUS POINTS IN THE CONDENSER TUBE

ITER.	QUALITY	CONDENSATE REYNOLDS NUMBER	CONDENSATION HEAT TRANSFER COEFFICIENT (BTU/HR-SQFT-DEG.F)	OVERALL HEAT TRANSFER COEFFICIENT (BTU/HR-SQFT-DEG.F)	HEAT RECOVERED (BTU/HR)	DIFFERENTIAL HEAT RECOVERED (BTU/HR)	ORDINATE
1	0.5263	1274	395.2	185.7	0.0	0.0	0.000047
2	0.5268	1249	396.2	185.7	372.9	372.9	0.000047
3	0.5273	1224	396.1	185.7	748.0	375.1	0.000046
4	0.5279	1199	396.0	185.7	1125.3	377.3	0.000046
5	0.5284	1174	395.9	185.6	1504.8	379.5	0.000046
6	0.5290	1148	395.8	185.6	1886.5	381.7	0.000045
7	0.5297	1122	395.6	185.6	2270.4	383.9	0.000045
8	0.5303	1097	395.4	185.5	2656.5	386.1	0.000045
9	0.5310	1071	395.1	185.5	3044.7	388.3	0.000045
10	0.5317	1045	394.9	185.4	3435.2	390.5	0.000044
11	0.5325	1019	394.6	185.3	3827.9	392.7	0.000044
12	0.5333	992	394.3	185.3	4222.8	394.9	0.000044

TABLE IV (Continued)

ITER.	QUALITY	CONDENSATE REYNOLDS NUMBER	CONDENSATION HEAT TRANSFER COEFFICIENT (BTU/HR-SQFT-DEG.F)	OVERALL HEAT TRANSFER COEFFICIENT (BTU/HR-SQFT-DEG.F)	HEAT RECOVERED (BTU/HR)	DIFFERENTIAL HEAT RECOVERED (BTU/HR)	ORDINATE
13	0.5342	966	393.9	185.2	4619.9	397.1	0.000044
14	0.5351	939	393.5	185.1	5019.1	399.2	0.000043
15	0.5360	912	393.0	185.0	5420.5	401.4	0.000043
16	0.5370	885	392.5	184.9	5824.1	403.6	0.000043
17	0.5381	858	391.9	184.7	6229.8	405.7	0.000043
18	0.5393	831	391.3	184.6	6637.7	407.8	0.000043
19	0.5405	804	390.6	184.5	7047.6	409.9	0.000042
20	0.5418	776	389.9	184.3	7459.6	412.0	0.000042
21	0.5432	748	389.0	184.1	7873.7	414.1	0.000042
22	0.5447	721	388.1	183.9	8289.8	416.1	0.000042
23	0.5464	693	387.1	183.7	8707.9	418.1	0.000042
24	0.5481	665	386.0	183.4	9127.9	420.0	0.000041
25	0.5500	637	384.8	183.1	9549.9	421.9	0.000041
26	0.5521	608	383.4	182.8	9973.6	423.8	0.000041

TABLE IV (Continued)

ITER.	QUALITY	CONDENSATE REYNOLDS NUMBER	CONDENSATION HEAT TRANSFER COEFFICIENT (BTU/HR-SQFT-DEG.F)	OVERALL HEAT TRANSFER COEFFICIENT (BTU/HR-SQFT-DEG.F)	HEAT RECOVERED (BTU/HR)	DIFFERENTIAL HEAT RECOVERED (BTU/HR)	ORDINATE
27	0.5544	580	381.9	182.5	10399.2	425.5	0.000041
28	0.5569	551	380.3	182.1	10826.4	427.2	0.000041
29	0.5596	523	378.4	181.7	11255.2	428.8	0.000041
30	0.5627	494	376.3	181.2	11685.5	430.3	0.000040
31	0.5660	465	374.0	180.7	12117.2	431.7	0.000040
32	0.5698	436	371.4	180.1	12550.0	432.9	0.000040
33	0.5740	407	369.9	179.7	12984.0	433.9	0.000040
34	0.5788	378	379.1	181.8	13419.5	435.6	0.000039
35	0.5844	349	389.4	184.2	13862.8	443.3	0.000039
36	0.5909	319	401.2	186.8	14314.5	451.6	0.000038
37	0.5987	288	414.9	189.7	14775.1	460.7	0.000037
38	0.6082	256	431.0	193.0	15245.8	470.7	0.000036
39	0.6200	224	450.5	196.8	15727.6	481.8	0.000035
40	0.6351	191	474.8	201.3	16221.9	494.3	0.000034

TABLE IV (Continued)

ITER.	QUALITY	CONDENSATE REYNOLDS NUMBER	CONDENSATION HEAT TRANSFER COEFFICIENT (BTU/HR-SQFT-DEG.F)	OVERALL HEAT TRANSFER COEFFICIENT (BTU/HR-SQFT-DEG.F)	HEAT RECOVERED (BTU/HR)	DIFFERENTIAL HEAT RECOVERED (BUT/HR)	ORDINATE (BTU/HR-SQFT)
41	0.7152	94	415.4	203.1	17683.8	499.8	0.000033
42	0.7732	58	464.1	214.1	18206.7	522.9	0.000031
43	0.8826	22	561.3	232.7	18761.5	554.8	0.000029
44	1.0000	0	INFINITY	397.6	19368.7	607.2	0.000017
45	0.9621	6	1503.7	283.6	18999.9	619.9	0.000024
46	1.0000	0	∞	349.5	19741.8	742.0	0.000019

TABLE V

FORCE TERMS AT VARIOUS POINTS IN THE CONDENSER TUBE

ITER.	FORCE CONSTANT (LBM/FT-HR**2	FRICTIONAL FORCE (LBM/FT-HR**2)	MOMENTUM FORCE (LBM/FT-HR**2)	ACCELERATION FORCE (LBM/FT-HR**2)	TOTAL FORCE (LBM/FT-HR**2)
1	0.1391 x 10^{9}	0.8390 x 10^{6}	0.0000 x 10^{0}	0.1656 x 10^{8}	0.1572 x 10^{8}
2	0.1340 x 10^{9}	0.8120 x 10^{6}	0.6307 x 10^{4}	0.1653 x 10^{8}	0.1573 x 10^{8}
3	0.1290 x 10^{9}	0.7851 x 10^{6}	0.6339 x 10^{4}	0.1650 x 10^{8}	0.1572 x 10^{8}
4	0.1240 x 10^{9}	0.7586 x 10^{6}	0.6370 x 10^{4}	0.1646 x 10^{8}	0.1571 x 10^{8}
5	0.1191 x 10^{9}	0.7322 x 10^{6}	0.6401 x 10^{4}	0.1643 x 10^{8}	0.1570 x 10^{8}
6	0.1143 x 10^{9}	0.7062 x 10^{6}	0.6431 x 10^{4}	0.1639 x 10^{8}	0.1569 x 10^{8}
7	0.1095 x 10^{9}	0.6804 x 10^{6}	0.6461 x 10^{4}	0.1635 x 10^{8}	0.1568 x 10^{8}
8	0.1048 x 10^{9}	0.6549 x 10^{6}	0.6490 x 10^{4}	0.1631 x 10^{8}	0.1566 x 10^{8}
9	0.1002 x 10^{9}	0.6297 x 10^{6}	0.6519 x 10^{4}	0.1626 x 10^{8}	0.1564 x 10^{8}
10	0.9572 x 10^{8}	0.6048 x 10^{6}	0.6548 x 10^{4}	0.1622 x 10^{8}	0.1562 x 10^{8}
11	0.9127 x 10^{8}	0.5802 x 10^{6}	0.6576 x 10^{4}	0.1617 x 10^{8}	0.1560 x 10^{8}
12	0.8691 x 10^{8}	0.5559 x 10^{6}	0.6603 x 10^{4}	0.1612 x 10^{8}	0.1557 x 10^{8}
13	0.8263 x 10^{8}	0.5319 x 10^{6}	0.6629 x 10^{4}	0.1607 x 10^{8}	0.1554 x 10^{8}

TABLE V (Continued)

ITER.	FORCE CONSTANT (LBM/FT-HR**2)	FRICTIONAL FORCE (LBM/FT-HR**2)	MOMENTUM FORCE (LBM/FT-HR**2)	ACCELERATION FORCE (LBM/FT-HR**2)	TOTAL FORCE (LBM/FT-HR**2)
14	0.7843×10^{8}	0.5083×10^{6}	0.6655×10^{4}	0.1601×10^{8}	0.1551×10^{8}
15	0.7433×10^{8}	0.4851×10^{6}	0.6679×10^{4}	0.1595×10^{8}	0.1547×10^{8}
16	0.7031×10^{8}	0.4622×10^{6}	0.6703×10^{4}	0.1589×10^{8}	0.1543×10^{8}
17	0.6638×10^{8}	0.4396×10^{6}	0.6726×10^{4}	0.1582×10^{8}	0.1539×10^{8}
18	0.6255×10^{8}	0.4175×10^{6}	0.6747×10^{4}	0.1575×10^{8}	0.1534×10^{8}
19	0.5881×10^{8}	0.3958×10^{6}	0.6767×10^{4}	0.1567×10^{8}	0.1529×10^{8}
20	0.5517×10^{8}	0.3744×10^{6}	0.6786×10^{4}	0.1559×10^{8}	0.1523×10^{8}
21	0.5163×10^{8}	0.3535×10^{6}	0.6803×10^{4}	0.1551×10^{8}	0.1516×10^{8}
22	0.4819×10^{8}	0.3331×10^{6}	0.6817×10^{4}	0.1542×10^{8}	0.1509×10^{8}
23	0.4485×10^{8}	0.3130×10^{6}	0.6831×10^{4}	0.1532×10^{8}	0.1501×10^{8}
24	0.4161×10^{8}	0.2935×10^{6}	0.6841×10^{4}	0.1521×10^{8}	0.1493×10^{8}
25	0.3849×10^{8}	0.2744×10^{6}	0.6848×10^{4}	0.1510×10^{8}	0.1483×10^{8}
26	0.3547×10^{8}	0.2558×10^{6}	0.6853×10^{4}	0.1498×10^{8}	0.1473×10^{8}
27	0.3257×10^{8}	0.2377×10^{6}	0.6854×10^{4}	0.1484×10^{8}	0.1461×10^{8}

TABLE V (Continued)

ITER.	FORCE CONSTANT (LBM/FT-HR**2)	FRICTIONAL FORCE (LBM/FT-HR**2)	MOMENTUM FORCE (LBM/FT-HR**2)	ACCELERATION FORCE (LBM/FT-HR**2)	TOTAL FORCE (LBM/FT-HR**2)
28	0.2978×10^{8}	0.2201×10^{6}	0.6851×10^{4}	0.1470×10^{8}	0.1448×10^{8}
29	0.2710×10^{8}	0.2031×10^{6}	0.6844×10^{4}	0.1454×10^{8}	0.1434×10^{8}
30	0.2454×10^{8}	0.1866×10^{6}	0.6831×10^{4}	0.1437×10^{8}	0.1419×10^{8}
31	0.2210×10^{8}	0.1707×10^{6}	0.6813×10^{4}	0.1418×10^{8}	0.1401×10^{8}
32	0.1973×10^{8}	0.1553×10^{6}	0.6787×10^{4}	0.1397×10^{8}	0.1382×10^{8}
33	0.1759×10^{8}	0.1406×10^{6}	0.6753×10^{4}	0.1373×10^{8}	0.1360×10^{8}
34	0.1551×10^{8}	0.1265×10^{6}	0.6723×10^{4}	0.1347×10^{8}	0.1335×10^{8}
35	0.1354×10^{8}	0.1128×10^{6}	0.6769×10^{4}	0.1318×10^{8}	0.1307×10^{8}
36	0.1166×10^{8}	0.9950×10^{5}	0.6809×10^{4}	0.1283×10^{8}	0.1274×10^{8}
37	0.9891×10^{7}	0.8672×10^{5}	0.6842×10^{4}	0.1244×10^{8}	0.1236×10^{8}
38	0.8234×10^{7}	0.7446×10^{5}	0.6861×10^{4}	0.1196×10^{8}	0.1190×10^{8}
39	0.6695×10^{7}	0.6275×10^{5}	0.6861×10^{4}	0.1140×10^{8}	0.1134×10^{8}
40	0.5281×10^{7}	0.5163×10^{5}	0.6831×10^{4}	0.1070×10^{8}	0.1065×10^{8}
41	0.4001×10^{7}	0.4115×10^{5}	0.6751×10^{4}	0.9813×10^{7}	0.9779×10^{7}

TABLE V (Continued)

ITER.	FORCE CONSTANT (LBM/FT-HR**2)	FRICTIONAL FORCE (LBM/FT-HR**2)	MOMENTUM FORCE (LBM/FT-HR**2)	ACCELERATION FORCE (LBM/FT-HR**2)	TOTAL FORCE (LBM/FT-HR**2)
42	0.2864×10^7	0.3136×10^5	0.6588×10^4	0.8657×10^7	0.8632×10^7
43	0.1882×10^7	0.2231×10^5	0.6270×10^4	0.7065×10^7	0.7049×10^7
44	0.1071×10^7	0.1403×10^5	0.5634×10^4	0.4707×10^7	0.4699×10^7
45	0.4513×10^6	0.5990×10^4	0.4187×10^4	0.7481×10^6	0.7463×10^6
46	0.1841×10^6	0.2009×10^4	0.3769×10^3	0.0000×10^0	0.0000×10^0

Diameter of the tube (14 BWG)	1.50000	INCHES	
Length of the tube	2.25	FEET	
Number of tubes required to recover	0.2500×10^7	BTU/HR	130

TABLE VI

CALCULATION OF DIMENSIONLESS FORCE TERMS

ITER.	QUALITY	DIMENSIONLESS F_F	DIMENSIONLESS F_M	DIMENSIONLESS F_A
1	0.5263	6.03×10^{-3}	0.00×10^{0}	1.19×10^{-1}
6	0.5290	6.18×10^{-3}	5.60×10^{-5}	1.43×10^{-1}
15	0.5360	6.53×10^{-3}	8.98×10^{-5}	2.15×10^{-1}
21	0.5432	6.85×10^{-3}	1.31×10^{-4}	3.00×10^{-1}
25	0.5500	7.13×10^{-3}	1.78×10^{-4}	3.92×10^{-1}
29	0.5596	7.49×10^{-3}	2.52×10^{-4}	5.36×10^{-1}
35	0.5849	8.33×10^{-3}	5.00×10^{-4}	9.73×10^{-1}
38	0.6082	9.04×10^{-3}	8.33×10^{-4}	1.45
42	0.7732	1.31×10^{-2}	5.26×10^{-3}	4.39
44	1.000	1.09×10^{-2}	2.04×10^{-3}	0.0

$$\text{Dimensionless } F' = \frac{F}{\left(\dfrac{8W_T^2}{\pi^2 \rho_V D^4}\right)}$$

A plot of F' versus quality is shown in Figure 21. Graphical evaluation of length is shown in Figure 22. The length of the tube from numerical analysis was 2.15 feet. The number of tubes required to recover 2.5×10^7 BTU/hr was found to be equal to 130.

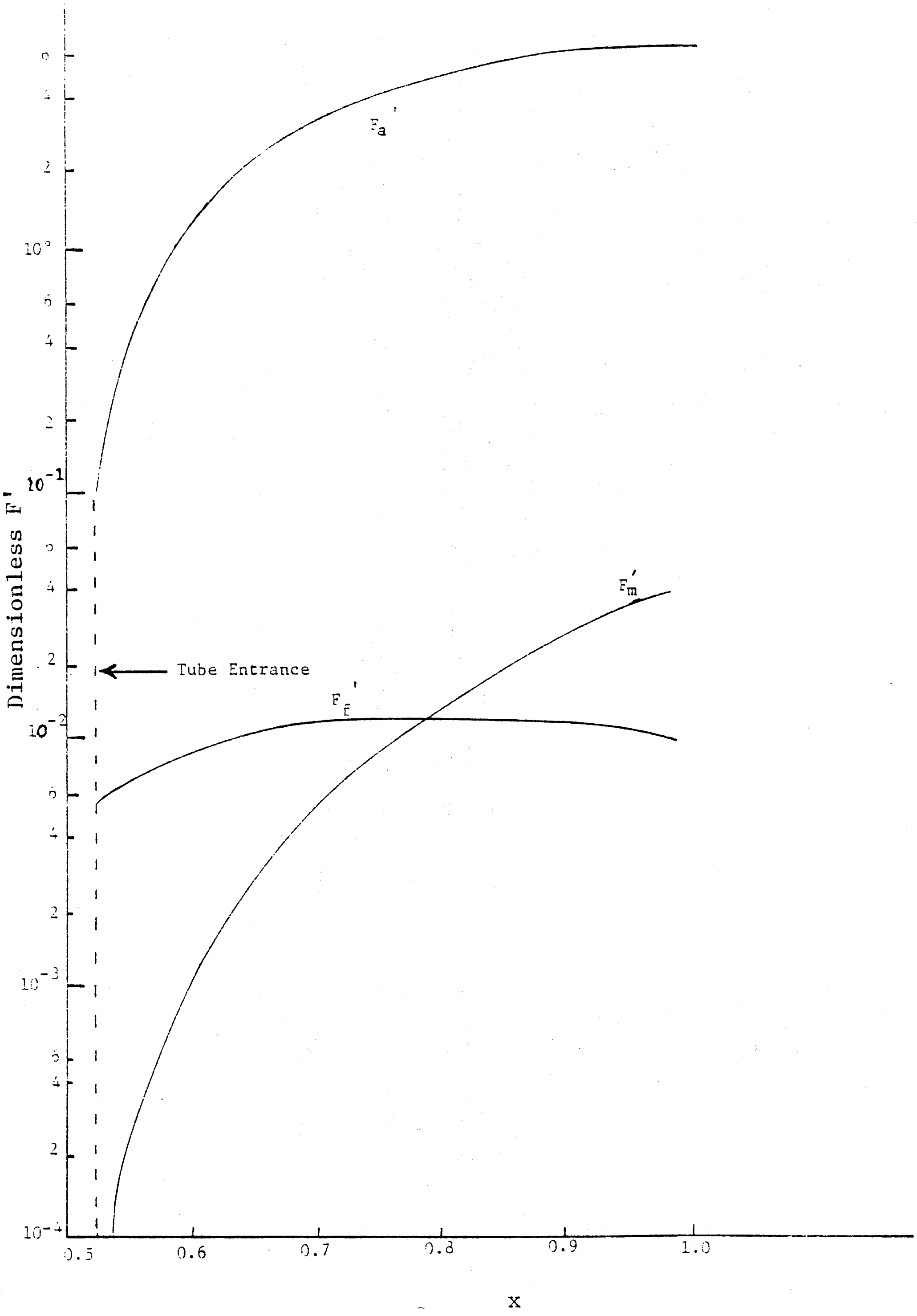
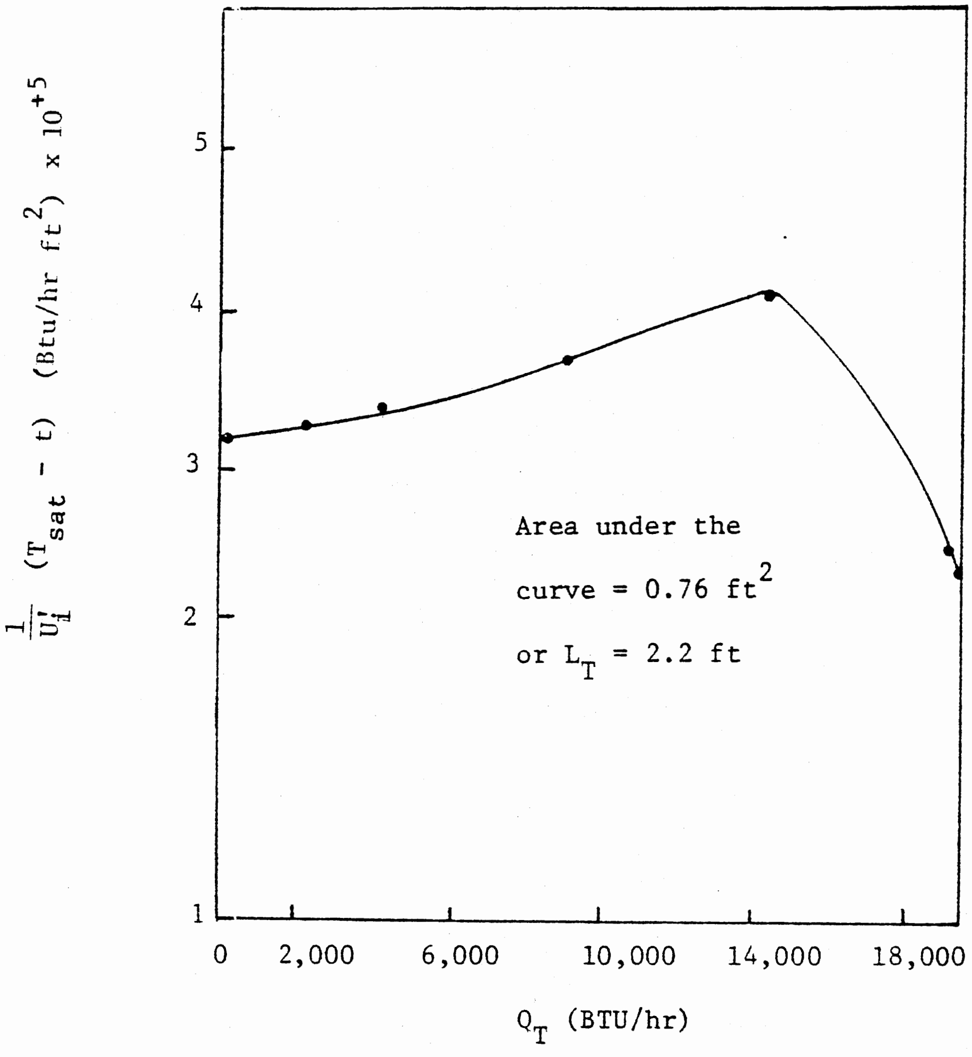


Figure 21. Dimensionless Forces versus Quality



Area under the curve = 0.76 ft^2 or L_T = 2.2 ft

Figure 22. Graphical Evaluation of Length of Tube.

Multicomponent Condensation

A mixture having the following composition (Table VII) is to be partially condensed from 180 F to 130 F at 150 psig in a shell and tube exchanger, arranged as a vertical reflux condenser. Cooling water enters at 85 F and leaves at 120 F. The tube diameter is 1.5 inches. The fouling rates are 0.0005 and 0.001 hr ft^2 F/BTU on the inside and outside respectively. The coolant coefficient is assumed to be 1000 BTU/hr ft^2 F.

It is required to calculate, the flooding velocity, the heat recovered per tube, length of the tube and the number of tubes required to recover 2.5×10^6 BTU/hr.

The preliminary computation, such as the vapor-liquid equilibrium curve, densities, enthalpies were determined for various intermediate points using the GPA*SIM (19) program. A summary of the results obtained are given in Tables VIII, IX, and X.

The physical properties are very nearly constant; hence, an average value is used throughout the entire vapor temperature range, and over the entire condensing range. These values are listed in Table VII. Surface tension, thermal conductivities and viscosities were obtained from the GPSA Engineering Data Book (20).

TABLE VII

INPUT DATA

Methane	1.79%	
Ethane	5.20%	
Propane	34.20%	
Iso-butane	16.65%	
N-butane	38.20%	
N-pentane	2.33%	
C_6^+	1.63%	
Vapor Inlet Temp.	180.00	Deg.F
Vapor outlet Temp.	130.00	Deg.F
Pressure	150.00	Psig.
Coolant Specific Heat	1.00	BTU/lbm Deg.F
Latent Heat of Condensation	132.00	BTU/lbm.
Liquid Density	35.00	Lbm/cu.ft.
Vapor Density	1.500	Lbm/cu.ft.
Vapor Viscosity	0.0242	Lbm/ft hr.
Liquid Viscosity	0.40	Lbm/hr ft.
Surface Tension	11.50	Dynes/cm.
Coolant Inlet Temp.	120.00	Deg.F
Coolant outlet Temp.	85.00	Deg.F
Liquid Thermal Conductivity	0.074	BTU/hr ft Deg.F
Wall Thermal Conductivity	26.00	BTU/hr ft Deg.F

TABLE VII (Continued)

Inside Fouling	0.0005	Hr sq.ft Deg.F/BTU
Outside Fouling	0.001	Hr sq.ft Deg.F/BTU
Liquid Specific Heat	0.50	BTU/lbm Deg.F
Coolant Heat Coefficient	1000.00	BTU/hr sq.ft Deg.F
Outside Tube Diameter	1.50	Inches
Wall Thickness	0.083	Inches
Vapor Thermal Conductivity	0.012	BTU/hr ft Deg.F
Vapor Specific Heat	0.57	BTU/lbm Deg.F

C_6^+ is assumed to have the properties of n-heptane throughout.

TABLE VIII

CONDENSING PATH (BASIS 100 LB.MOLES)

ITER.	TEMP. °F	CH_4		C_2H_6		C_3H_8		iC_4H_{10}		nC_4H_{10}		nC_5H_{12}		nC_7H_{16}		ΣV	ΣL
		L	V	L	V	L	V	L	V	L	V	L		L	V		
1	180	0.00	1.79	0.00	5.20	0.00	34.20	0.00	16.65	0.00	38.20	0.00	2.33	0.00	1.63	100.00	0.00
2	170	0.00	1.79	0.02	5.18	0.29	33.91	0.26	16.39	0.74	37.46	0.10	2.23	0.29	1.34	98.30	1.70
3	165	0.01	1.78	0.06	5.14	0.88	33.32	0.79	15.86	2.24	35.96	0.29	2.04	0.68	0.95	95.06	4.94
4	160	0.01	1.78	0.12	5.08	1.81	32.39	1.60	15.05	4.51	33.69	0.53	1.78	1.00	0.63	90.40	9.60
5	155	0.02	1.77	0.22	4.98	3.34	30.86	2.86	13.79	7.92	30.28	0.88	1.45	1.24	0.39	83.51	16.49
6	150	0.04	1.75	0.40	4.80	5.74	28.48	4.66	11.99	12.60	25.60	1.25	1.08	1.40	0.23	73.90	26.10
7	145	0.07	1.72	0.66	4.54	9.06	25.14	6.86	9.79	17.99	20.21	1.59	0.74	1.50	0.13	62.27	37.73
8	140	0.12	1.67	1.03	4.17	13.04	21.16	9.12	7.53	23.19	15.01	1.84	0.49	1.56	0.07	50.12	49.88
9	135	0.18	1.61	1.49	3.71	17.29	16.91	11.15	5.50	27.59	10.61	2.02	0.31	1.59	0.04	38.69	61.31
10	130	0.28	1.51	2.04	3.16	21.40	12.80	12.83	3.82	31.02	7.18	2.13	0.20	1.61	0.02	28.69	71.30

Entering 100 lb. moles of Vapor	Leaving 28.69 lb. moles
or	
Entering 100 % (wt) Vapor	Leaving 25.7% (wt)

TABLE IX

PHYSICAL PROPERTIES AT VARIOUS POINTS IN THE CONDENSER TUBE

ITER.	TEMP.	DENSITY (lbm/ft^3)		Mol. wt (lbm/lbmole)	
	°F	Liquid	Vapor	Liquid	Vapor
1	180	36.35	1.492	64.21	52.12
2	170	36.3	1.52	63.53	51.90
3	165	35.97	1.53	61.87	51.60
4	160	35.64	1.53	60.25	51.26
5	155	35.32	1.53	58.75	50.81
6	150	35.04	1.53	57.47	50.23
7	145	34.8	1.52	56.40	49.50
8	140	34.6	1.507	55.60	48.60
9	135	34.4	1.48	54.90	47.70
10	130	34.3	1.45	54.30	46.70

For this hydrocarbon mixture, the average molecular weight is taken as 52 lbm/lbmole (Figure

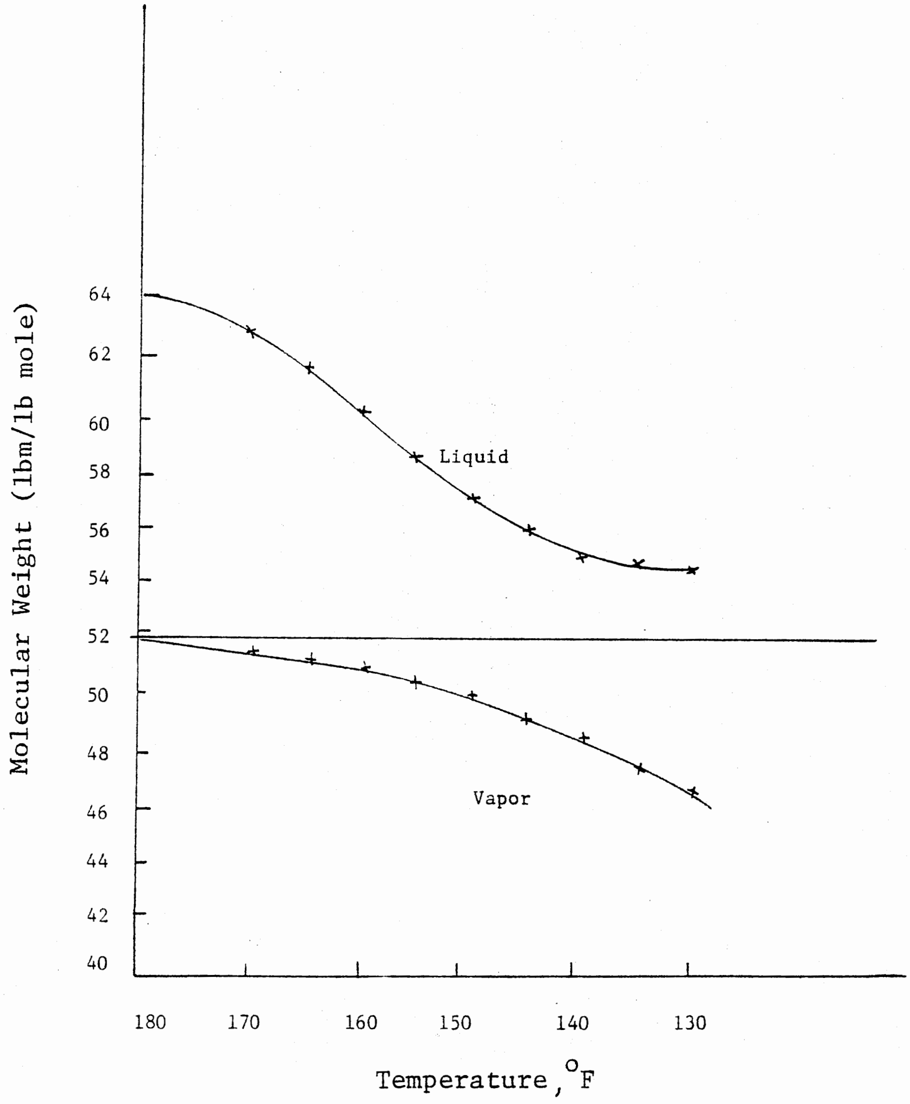


Figure 23. Estimation of Average Molecular Weight.

TABLE X

ENTHALPY VALUES AT VARIOUS POINTS IN THE CONDENSER TUBE

ITER.	°F TEMP.	(KBTU/lbmole) TOTAL ENTHALPY	(KBTU/lbmole) ENTHALPY OF VAPOR
1	180	9.157	9.157
2	170	8.75	8.86
3	165	8.37	8.69
4	160	7.89	8.51
5	155	7.26	8.33
6	150	6.44	8.13
7	145	5.49	7.92
8	140	4.51	7.71
9	135	3.59	7.49
10	130	2.76	7.27

$$\text{Heat recovered/tube} = (9.157-2.76)\ \frac{\text{KBTU}}{\text{lbmole}} \times 1000 \times \frac{1}{52\ \frac{\text{lbm}}{\text{lbmole}}} \times \begin{matrix}\text{Vapor}\\ \text{Condensed}\end{matrix}$$

$$= 123\ \frac{\text{BTU}}{\text{lbm}} \times \text{Vapor Condensed/tube}\ \frac{\text{lbm}}{\text{hr}}$$

TABLE XI

PRELIMINARY CALCULATIONS

Flooding Velocity	2.5	FT/SEC.
Operating Velocity	6294.0	FT/HR.
Cross Sectional Area/Tube	0.0097	SQFT
Vapor Condenser/Tube	91.6	LB/HR
Heat Duty/Tube	11259.0	BTU/HR
Coolant Rate/Tube	321.6	LB/HR
Fraction Condensed	0.740	

TABLE XII

FLOW RATE CALCULATIONS AT VARIOUS POINTS IN THE CONDENSER TUBE

ITER	BULK VAP.TEMP. (FAHRENHEIT)	COOLANT TEMP. (FAHRENHEIT)	LENGTH (FEET)	VAP.RATE (LB/HR)	LIQ.RATE (LB/HR)	COND.RATE (LB/HR)	TOTAL RATE (LB/HR)
1	180.0000	120.0000	0.000	91.520	67.999	0.000	159.519
2	170.0000	117.7732	2.148	89.625	66.105	1.894	155.730
3	165.0000	115.6941	3.320	86.157	62.636	3.469	148.793
4	160.0000	113.0678	4.492	81.361	57.840	4.796	139.201
5	155.0000	109.6209	5.664	74.506	50.986	6.855	125.492
6	150.0000	105.1344	7.031	65.180	41.660	9.326	106.840
7	145.0000	99.9366	8.398	54.125	30.604	11.056	84.729
8	140.0000	94.5748	9.570	42.822	19.301	11.303	62.123
9	135.0000	89.5411	10.742	32.416	8.896	10.406	41.312
10	130.0000	84.9999	11.328	23.521	0.000	8.896	23.521

TABLE XIII

HEAT TRANSFER CALCULATIONS AT VARIOUS POINTS IN THE CONDENSER TUBE

ITER	QUALITY	CON.RE.NO.	COND.HT.TR.COEFF. (BTU/HR-SQFT-DEG.F)	OV.HT.TR.COEFF. (BTU/HR-SQFT-DEG.F)	HT.RECOV. (BTU/HR)	DIFF.HT.RECOV. (BTU/HR)	ORDINATE
1	0.57372	1947.1140	420.6885	204.4026	0.0000	0.0000	0.016667
2	0.57552	1892.8670	419.4624	204.1128	716.3167	716.3167	0.001009
3	0.57904	1793.5470	417.0256	203.5341	1385.1120	668.7961	0.000575
4	0.58448	1656.2270	413.1907	202.6163	2229.9090	844.7969	0.000514
5	0.59371	1459.9420	406.5662	201.0102	3338.7040	1108.7940	0.000388
6	0.61007	1192.9020	394.6055	198.0423	4781.8940	1443.1900	0.000318
7	0.63880	876.3325	373.3811	192.5493	6453.8900	1671.9960	0.000271
8	0.68930	552.6868	336.0652	182.1208	8178.6790	1724.7890	0.000229
9	0.78467	254.7232	265.1565	159.0685	9797.8750	1619.1950	0.000264
10	1.00000	0.0000	INFINITY	397.5745	11258.6600	1460.7920	0.000147

TABLE XIV

FORCE TERMS AT VARIOUS POINTS IN THE CONDENSER TUBE

ITER	FORCE CONST. (LBF/FT**2)	FRICT.FORCE (LBF/FT**2)	MOMENT.FORCE (LBF/FT**2)	ACCEL.FORCE (LBF/FT**2)	TOTAL FORCE (LBF/FT**2)
1	0.375930E 17	0.336608E 15	0.000000E 00	0.134051E 17	0.130685E 17
2	0.358283E 17	0.322926E 15	0.184438E 12	0.133152E 17	0.129924E 17
3	0.327074E 17	0.298520E 15	0.605117E 12	0.131398E 17	0.128419E 17
4	0.286266E 17	0.266159E 15	0.817458E 12	0.128722E 17	0.126068E 17
5	0.232655E 17	0.222726E 15	0.112192E 13	0.124274E 17	0.122058E 17
6	0.168636E 17	0.169069E 15	0.122743E 13	0.116661E 17	0.114982E 17
7	0.106059E 17	0.116789E 15	0.133907E 13	0.104070E 17	0.102946E 17
8	0.570158E 16	0.669184E 14	0.144324E 13	0.840519E 16	0.833971E 16
9	0.252136E 16	0.325585E 14	0.114846E 13	0.522310E 16	0.519169E 16
10	0.817292E 15	0.570524E 13	0.590394E 13	0.000000E 00	0.198707E 12

TABLE XV

CALCULATION OF DIMENSIONLESS FORCE TERMS

ITER.	QUALITY	DIMENSIONLESS F_f'	DIMENSIONLESS F_n'	DIMENSIONLESS F_a'
1	.5737	8.96×10^{-3}	0.00×10^{0}	3.47×10^{-1}
2	.5755	9.02×10^{-3}	5.14×10^{-6}	3.70×10^{-1}
3	.5790	9.13×10^{-3}	1.85×10^{-5}	4.01×10^{-1}
4	.5845	9.29×10^{-3}	2.86×10^{-5}	4.49×10^{-1}
5	.5950	9.57×10^{-3}	4.82×10^{-5}	5.34×10^{-1}
6	.5937	1.00×10^{-2}	7.30×10^{-5}	6.92×10^{-1}
7	.6100	1.07×10^{-2}	1.26×10^{-4}	9.81×10^{-1}
8	.6388	1.17×10^{-2}	2.53×10^{-4}	1.47
9	.7847	1.29×10^{-2}	4.55×10^{-4}	2.07
10	1.000	6.98×10^{-3}	7.22×10^{-3}	0.00

$$\text{Dimensionless } F' = \frac{F}{\left(\dfrac{8W_T^2}{\pi^2 \rho_v D^4}\right)}$$

The above is shown in Figure 25. Figure 26 is the graphical evaluation of the length of the tube. The length of the tube from numerical analysis was 11.33 feet. The number of tubes required to recover 2.5 x 10^7 BTU/hr was found to be equal to 222.

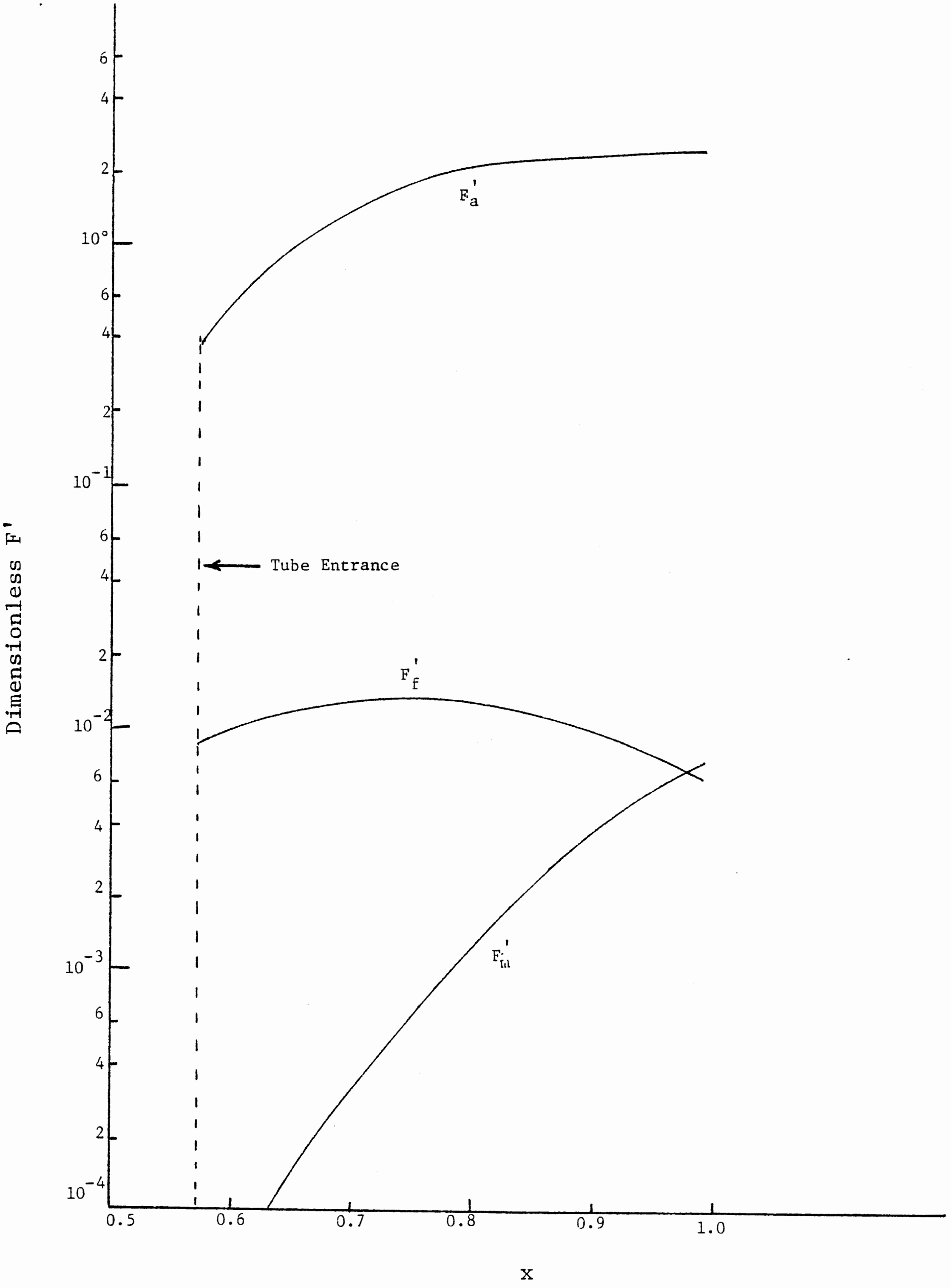


Figure 2 4. Dimensionless Forces versus Quality

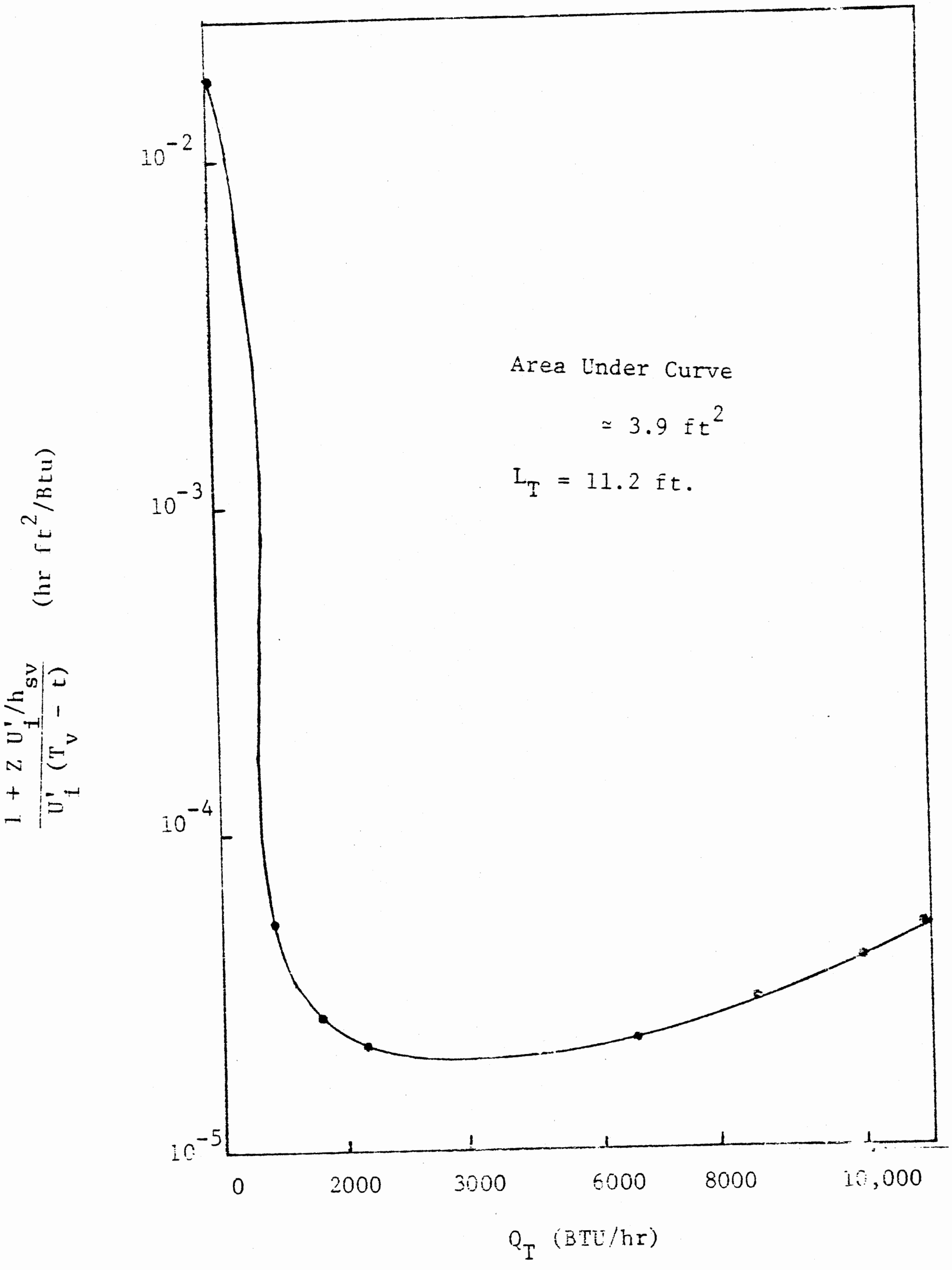
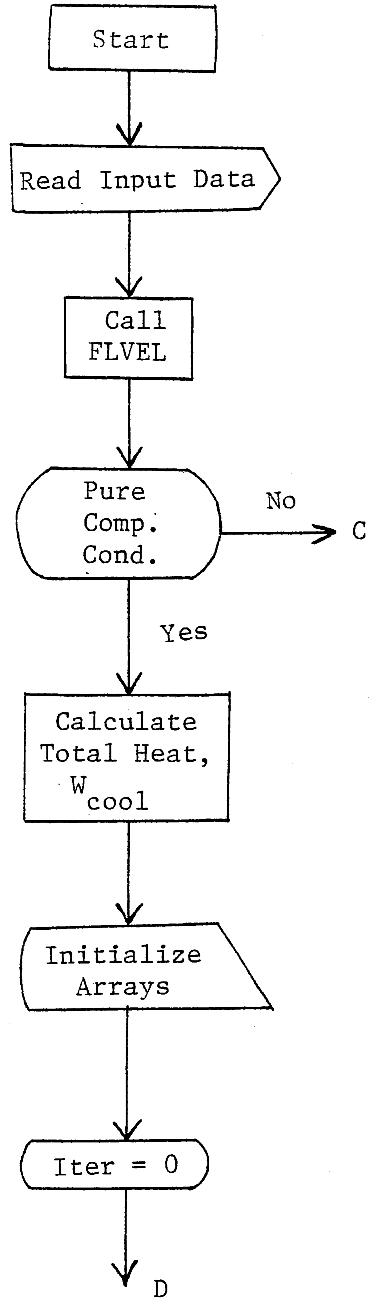
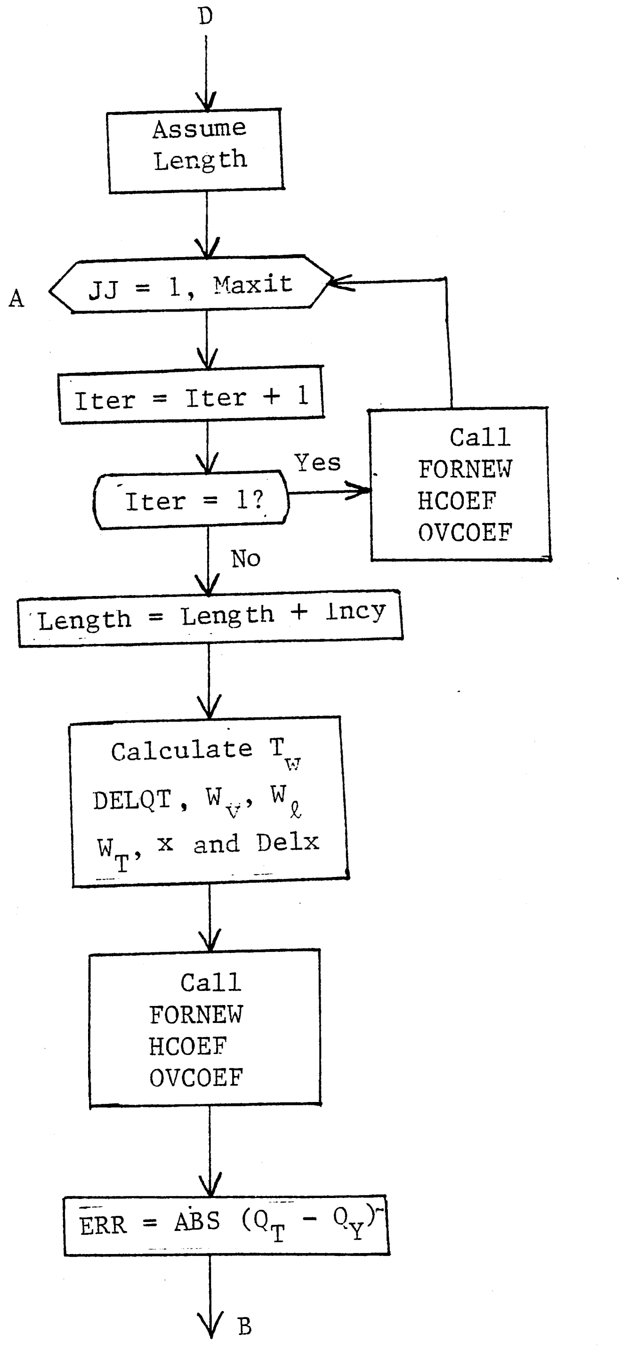


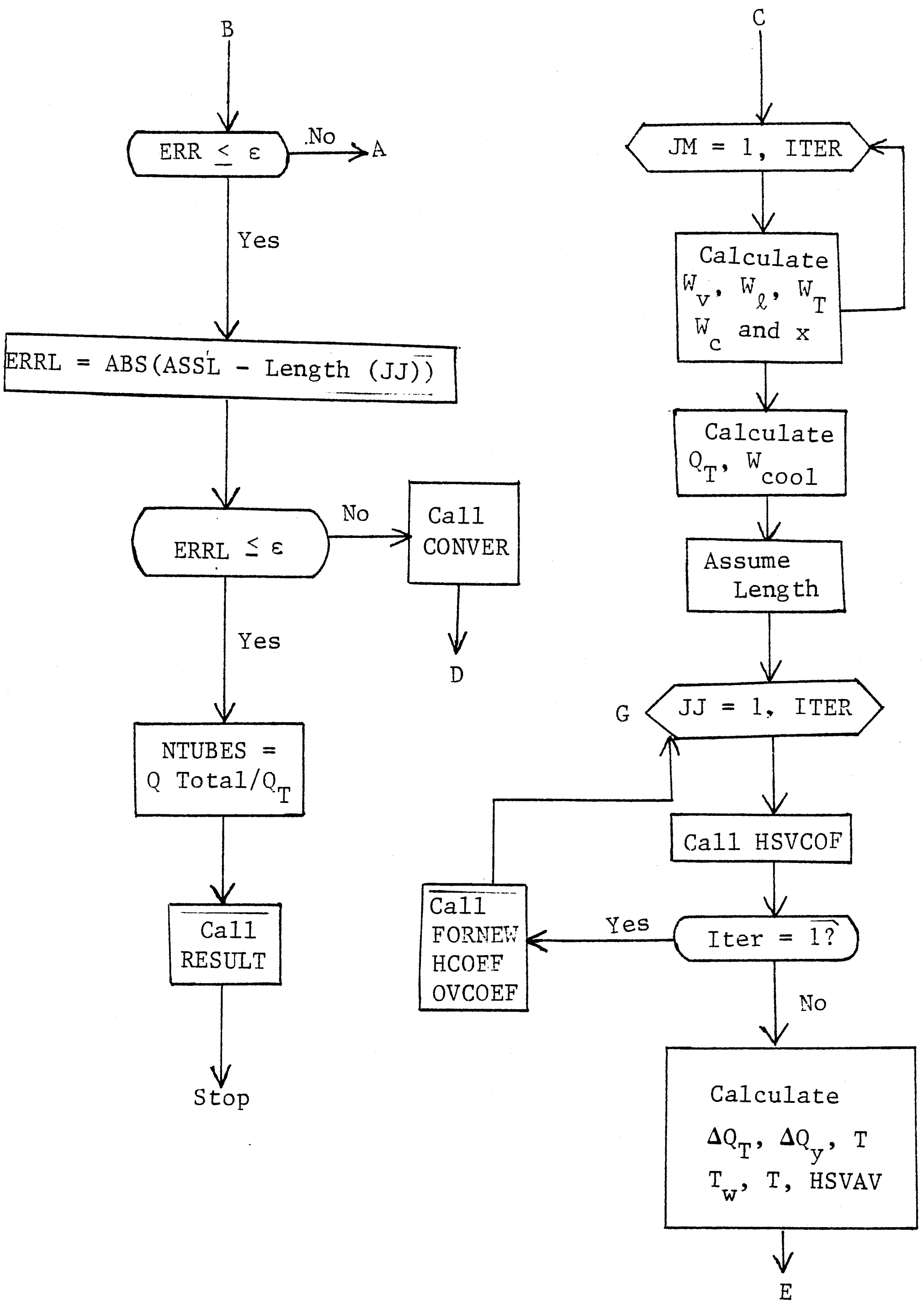
Figure 25. Graphical Evaluation of Length of the Tube.

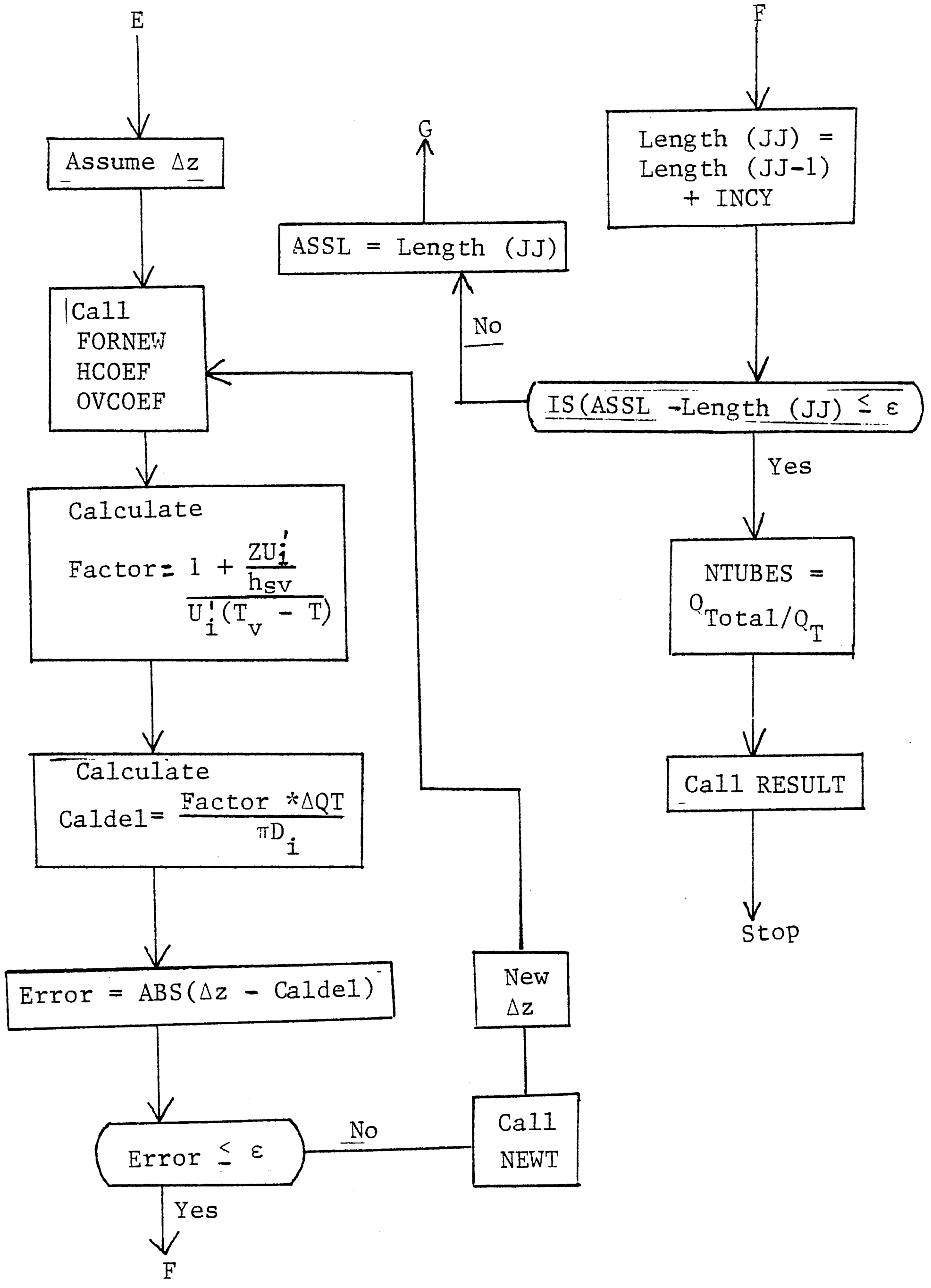
APPENDIX B

FLOW SHEET FOR COMPUTER PROGRAM


Start
Read Input Data
Call FLVEL
Pure Comp. Cond.
No
C
Yes
Calculate Total Heat, W_{cool}
Initialize Arrays
Iter = 0
D


D
Assume Length
A
JJ = 1, Maxit
Iter = Iter + 1
Iter = 1?
Yes
Call FORNEW HCOEF OVCOEF
No
Length = Length + Incy
Calculate T_W DELQT, W_V, W_ℓ W_T, x and Delx
Call FORNEW HCOEF OVCOEF
ERR = ABS $(Q_T - Q_Y)$
B


B
ERR ≤ ε
No
A
Yes
ERRL = ABS(ASSL - Length (JJ))
ERRL ≤ ε
No
Call CONVER
D
Yes
NTUBES = Q Total/Q_T
Call RESULT
Stop
C
JM = 1, ITER
Calculate W_v, W_ℓ, W_T W_c and x
Calculate Q_T, W_{cool}
Assume Length
G
JJ = 1, ITER
Call HSVCOF
Iter = 1?
Yes
Call FORNEW HCOFF OVCOEF
No
Calculate ΔQ_T, ΔQ_y, T T_w, T, HSVAV
E


E
Assume Δz
Call
FORNEW
HCOEF
OVCOEF
Calculate
Factor= 1 + ZU'i / hsv / U'i(Tv - T)
Calculate
Caldel= Factor *ΔQT / πDi
Error = ABS(Δz - Caldel)
Error ≤ ε
Yes
F
No
Call
NEWT
New
Δz
G
ASSL = Length (JJ)
No
F
Length (JJ) =
Length (JJ-1)
+ INCY
IS(ASSL -Length (JJ) ≤ ε
Yes
NTUBES =
QTotal/QT
Call RESULT
Stop

APPENDIX C

PROGRAM DESCRIPTIONS

SUMMARY OF PROGRAM

The main program calculates the mass flow rates of the vapor and liquid, the qualities, coolant and wall temperatures, heat recovered and the length of the tube for each Δz increment.

Subroutine Read 1

The input data consisting of the inlet conditions and the various physical properties are read in by this Subroutine.

Subroutine FLVEL

This Subroutine calculates the flooding velocity of the vapor using Diehl-Koppany Correlation.

Subroutine HCOEF

Condensation heat transfer coefficients using the modified Carpenter - Colburn equation and the Nusselt equation are computed in the Subroutine. The higher number is taken as the point value for the condensing coefficient.

Subroutine FORNEW

This Subroutine calculates the total shear stress (F_o) by evaluating the three components F_a, F_f and F_m. The equations used are those of Soliman et al.

Subroutine HSVCOF

The vapor heat transfer coefficient in the case of multicomponent condensation is calculated in this Subroutine using equation 3.

Subroutine OVCOEF

The overall heat transfer coefficient with respect to the inner area is computed.

Subroutine NEWT and Subrouting CONVER

NEWT estimates the new guess of Δz for the multicomponent condensation. CONVER gives the new guess of length of tube for pure component condensation. Both Subroutines use binary chop method for convergence.

Subroutine CUNIT

Converts U.S. Customary Units to SI Units.

Subroutine RESULT

Prints the calculated variables after convergence is met. All point values are printed out.

INPUT CODES FOR PROGRAM

Card Set 1

Number of cards = 1

M = 0 Pure component condensation

= 1 Multicomponent condensation

L units = 0 U.S. Customary Units

= 1 SI units

FORMAT (2I2)

Card Set 2

Number of cards = 1

D = Inner tube diameter

OD = Outer tube diameter

PI = Value of π

RLG = Liquid to gas ratio

SIGMA = Surface tension

HW = Coolant heat transfer coefficient

T_1, T_2 = Inlet and outlet coolant temperatures respectively

Conv = 2520.

FORMAT (9F8.0)

Card Set 3

Number of cards = 1

CPC = Specific heat of coolant

PR = Pressure

AKW = Thermal conductivity of tube wall

WALLTH = Wall thickness

RFI, RFO = Inside and outside fouling factors of tube, respectively

G = Gravitational constant

FORMAT (F4.0, 5F8.0, E15.8)

Card Set 4

Number of cards = 1

AMUV, AMUL = Viscosities of vapor and liquid, respectively

CPL = Specific heat of liquid

AKL = Thermal conductivity of liquid

ALAMDA = Latent heat of condensation

RHOG, RHOL = Densities of vapor and liquid, respectively

FORMAT (7F10.0)

Card Set 5 (Only if M = 0)

Number of cards = 1

TSAT = Saturation temperature of vapor at PR

INCY = Increment in length

MAXIT = Maximum number of iterations

FORMAT (2F10.0,I3)

Card Set 6

Number of cards = 1

UPLT, LOWLT = Upper limit for tube length and lower limit for tube length

FORMAT (2F10.0)

Card Set 7 (Only if M = 0)

Number of cards = 1

COMP = Name of the pure component being condensed

FORMAT (3Af)

Card Set 8 (Only if M = 1)

Number of cards = 1

NCOMPS = Number of components for multicomponent condensation

ITER = Number of temperature increments

AVMWT = Average molecular weight

CPG = Specific heat for vapor

AKV = Thermal conductivity of vapor

FORMAT (2I3, 3F10.0)

Card Set 9 (Only if M = 1)

Number of cards = ITER

VAPTEM = Bulk vapor temperature for each increment

WTFRVA = Weight fraction of vapor for each increment (precalculated)

ENTHV = Vapor enthalpy

ENTHF = Total enthalpy

FORMAT (4F10.0)

Card Set 10 (Only if M = 1)

Number of cards = NCOMPS

COMPS	= Component name
AMOLFR	= Mole percent of the component at the inlet
FORMAT	(3A4, F5.0)

Card Set 11

Number of cards = 1

QTOTAL	= Total heat duty (in all tubes)
FORMAT	(E20.10)

APPENDIX D

PROGRAM LISTING

```
C                                                                       REFC0001
C                                                                       REFC0002
C     PROGRAM CALCULATES THE FLOODING VELOCITY, HEAT DUTY               REFC0003
C     RECOVERED PER TUBE AND THE LENGTH OF THE TUBE.                    REFC0004
C     IN A REFLUX CONDENSER.                                            REFC0005
C                                                                       REFC0006
C     'M' = 0  DENOTES PURE COMPONENT CONDENSATION                      REFC0007
C     'M' = 1  DENOTES MULTI-COMPONENT CONDENSATION                     REFC0008
C     LUNITS=0  DENOTES OUTPUT IN BRITISH UNITS                         REFC0009
C     LUNITS=1  DENOTES OUTPUT IN S I UNITS                             REFC0010
C                                                                       REFC0011
C     DEFINITION OF ALL THE VARIABLES USED IN THE PROGRAM               REFC0012
C                                                                       REFC0013
C     D-----------------------INSIDE DIA. OF TUBE (INCHES)              REFC0014
C     DI----------------------INSIDE DIA. OF TUBE (FEET)                REFC0015
C     OD----------------------OUTSIDE DIA. OF TUBE (INCHES)             REFC0016
C     VF----------------------FLOODING VELOCITY (FT/SEC)                REFC0017
C     V-----------------------OPERATING VELOCITY (FT/HR)                REFC0018
C     AREA--------------------CROSS-SECT. AREA (FT**2)                  REFC0019
C     WV----------------------VAPOR FLOW RATE (LB/HR)                   REFC0020
C     WL----------------------LIQUID FLOW RATE (LB/HR)                  REFC0021
C     WT----------------------TOTAL FLOW RATE (LB/HR)                   REFC0022
C     WTC---------------------CONDENSATE FLOW RATE (LB/HR)              REFC0023
C     WCOOL-------------------COOLANT FLOW RATE (LB/HR)                 REFC0024
C     AMUV--------------------VAPOR OR GAS VISCOSITY (LB/FT-HR)         REFC0025
C     AMUL--------------------LIQUID VISCOSITY (LB/FT-HR)               REFC0026
C     CPC---------------------SP. HT. OF COOLANT (BTU/LB-DEG F)         REFC0027
C     CPG---------------------SP. HT. OF GAS/VAPOR (BTU/LB-DEG F)       REFC0028
C     CPL---------------------SP. HT. OF LIQUID (BTU/LB-DEG F)          REFC0029
C     AKL---------------------THERMAL COND. OF LIQ. (BTU/HR-FT DEG F)   REFC0030
C     AKW---------------------THERMAL COND. OF WALL (BTU/HR-FT DEG F)   REFC0031
C     AKV---------------------THERMAL COND. OF VAPOR (BTU/HR-FT DEG F)  REFC0032
C     ALAMDA------------------LATENT HEAT OF COND. (BTU/LB)             REFC0033
C     RLG---------------------LIQ. TO GAS RATIO (DIMENSIONLESS)         REFC0034
C     RHOG--------------------GAS OR VAPOR DENSITY (LB/FT**3)           REFC0035
C     RHOL--------------------LIQUID DENSITY (LB/FT**3)                 REFC0036
C     SIGMA-------------------SURFACE TENSION OF CONDENSATE (DYNES/CM)  REFC0037
C     SIGMA1------------------SURFACE TENSION (DIMENSIONLESS)           REFC0038
C     T1----------------------INLET COOLANT TEMP (DEG F)                REFC0039
C     T2----------------------OUTLET COOLANT TEMP (DEG F)               REFC0040
C     T-----------------------TEMP. OF COOLANT AT ANY POINT (DEG F)     REFC0041
C     TSAT--------------------SATURATION TEMP. OF PURE VAPOR (DEG F)    REFC0042
C     VAPTEM------------------BULK VAP. TEMP. (DEG F)                   REFC0043
C     PR----------------------PRESSURE (PSIG)                           REFC0044
C     ASSL--------------------ASSUMED LENGTH (FT)                       REFC0045
C     LENGTH------------------CALCULATED LENGTH (FT)                    REFC0046
C     INCY--------------------ASSUMED INCREMENT (FT)                    REFC0047
C     CALDEL------------------CALCULATED INCREMENT (FT)                 REFC0048
C     QTOTAL------------------TOTAL HEAT RECOVERED (BTU/HR)             REFC0049
C     QT----------------------HEAT RECOVERED PER TUBE (BTU/HR)          REFC0050
C     QY----------------------HEAT RECOVERED UPTO THAT POINT (BTU/HR)   REFC0051
C     PI----------------------3.4174                                    REFC0052
C     CONV--------------------CONVERTING FACTOR(70%FLOODING VELOCITY)   REFC0053
C     FDF---------------------FORCE DUE TO FRICTION (LB/FT-HR**2)       REFC0054
C     FDM---------------------FORCE DUE MOMENTUM CHANGES (LB/FT-HR**2)  REFC0055
C     FDA---------------------NEGATIVE ACC. FORCE (LB/FT-HR**2)         REFC0056
C     FO----------------------TOTAL FORCE (LB/FT-HR**2)                 REFC0057
C     AF------ ---------------8*WT**2/PI**2(RHOG)DI**4 (LB/FT-HR**2)    REFC0058
C     FRT---------------------FROUDE NO. (DIMENSIONLESS)                REFC0059
C     PRL---------------------PRANDTL NO. (DIMENSIONLESS)               REFC0060
C     RET---------------------REYNOLDS NO. BASED ON TOT. RATE           REFC0061
C     RECNO-------------------REYNOLDS NO. OF CONDENSATE                REFC0062
C     G-----------------------GRAVITY FORCE (LB-FT/LBF-HR**2)           REFC0063
C     BETA--------------------VELOCITY (DIMENSIONLESS)                  REFC0064
C     WALLTH------------------WALL THICKNESS (INCHES)                   REFC0065
C     RFI,RFO-----------------FOULING RESISTANCES (HR-FT**2 DEG F/BTU)  REFC0066
C     HW----------------------COOL HT. TRANS. COEFF (BTU/HR-FT**2 DEG F)REFC0067
C     HC----------------------COLBURN HT. TR. COEFF (BTU/HR-FT**2 DEG F)REFC0068
C     HN----------------------NUSSELT HT.TR. COEFF (BTU/HR-FT**2 DEG F) REFC0069
C     HY----------------------COND. HT. TR. COEFF (BTU/HR-FT**2 DEG F)  REFC0070
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C     HSV---------------------SENSIBLE HT.TR.COEFF (BTU/HR-FT**2 DEG F) REFC0071
C     HSVAV-------------------AV. SENS. HT.TR. COEF (BTU/HR-FT**2 DEG F)REFC0072
C     UO----------------------OVERALL HT.TR. COEFF (BTU/HR-FT**2 DEG F) REFC0073
C     X-----------------------QUALITY (DIMENSIONLESS)                   REFC0074
C     COMPS-------------------NO. OF COMPONENTS (FOR M=1)               REFC0075
C     COMP--------------------PURE COMPONENT                            REFC0076
C     DELQT-------------------HT. RECOVD. PER INCREMENT (BTU/HR)        REFC0077
C     DELQSV------------------SENSIBLE HT. LOAD PER INCREMENT (BTU/HR)  REFC0078
C     Z-----------------------RATIO OF DELQSV/DELQT                     REFC0079
C     AMOLFR------------------MOLE % OF EACH COMPONENT IN FEED          REFC0080
C     WTFRVA------------------WT. FRACTION OF VAP. MIX. AT EVERY TEMP.  REFC0081
C     AVMWT-------------------AVERAGE MOLECULAR WEIGHT (LBM/LB MOLE)    REFC0082
C     ENTHF-------------------FEED ENTHALPY (BTU/LB MOLE)               REFC0083
C     ENTHV-------------------VAPOR ENTHALPY (BTU/LBM)                  REFC0084
C     ITER--------------------NO. OF ITERATIONS                         REFC0085
C     MAXIT-------------------MAXIMUM NO. OF ITERATIONS                 REFC0086
C     UPLT--------------------MAXIMUM POSSIBLE LENGTH OF TUBE           REFC0087
C     LOWLT-------------------MINIMUM POSSIBLE LENGTH OF TUBE           REFC0088
C     NTUBES------------------NO. OF TUBES REQUIRED                     REFC0089
C                                                                       REFC0090
C                                                                       REFC0091
      REAL LENGTH                                                       REFC0092
      REAL INCY,LOWLT                                                   REFC0093
C                                                                       REFC0094
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)                REFC0095
      COMMON/C2/AMUV,BETA,PI,FO(99),TW(99),QY(101),X(99),WT(99),HN(99)  REFC0096
      COMMON/C3/AMUL,AKL,HY(99),CPL,ASSL,WV(99),T(99),Q(99),TWALL(99)   REFC0097
      COMMON/C4/T1,T2,TSAT,D,QT,ALAMDA,HW,WC,P,WL(99),DELX              REFC0098
      COMMON/C5/NA,PR,UO(99),AKW,WALLTH,RFI,RFO,G,COMP(99),AVMWT,CONV,ODREFC0099
      COMMON/C6/V,AREA,HC(99),COMPS(10,3),CPG,CPC,AKV                   REFC0100
      COMMON/C7/ITER,M,VAPTEM(99),ENTHV(99),ENTHF(99),WTFRVA(99)        REFC0101
      COMMON/C8/DELQSV(99),DELQT(99),RECNO(99),WTC(99),FACTOR(101)      REFC0102
      COMMON/C9/HSV(99),HSVAV(99),FDF(99),FDM(99),FDA(99),AF(99),WCOOL  REFC0103
      COMMON/C10/NCOMPS,LENGTH(125),CALDEL,INCY,MAXIT,LENT(125)         REFC0104
      COMMON/C11/LOWLT,UPLT,HALF,AMOLFR(20),QTOTAL,NTUBES,LUNITS        REFC0105
C                                                                       REFC0106
C                                                                       REFC0107
C                                                                       REFC0108
      READ (5,1) M,LUNITS                                               REFC0109
  1   FORMAT(2I2)                                                       REFC0110
      CALL READ1                                                        REFC0111
C                                                                       REFC0112
C                                                                       REFC0113
C                                                                       REFC0114
      DI=D/12.0                                                         REFC0115
C                                                                       REFC0116
C     SUBROUTINE FLVEL CALCULATES THE FLOODING VELOCITY                 REFC0117
C                                                                       REFC0118
      CALL FLVEL                                                        REFC0119
C                                                                       REFC0120
C     OPERATING VELOCITY IS TAKEN AS 70% FLOODING VELOCITY              REFC0121
C                                                                       REFC0122
C                                                                       REFC0123
      V=VF*CONV                                                         REFC0124
      AREA=(PI*(DI**2))/4.0                                             REFC0125
      WV(1)=V*AREA*RHOG                                                 REFC0126
C                                                                       REFC0127
C                                                                       REFC0128
      IF(M.EQ.1) GO TO 2                                                REFC0129
C                                                                       REFC0130
C                                                                       REFC0131
      QT=WV(1)*ALAMDA                                                   REFC0132
      WCOOL=QT/(CPC*ABS(T2-T1))                                         REFC0133
C                                                                       REFC0134
C                                                                       REFC0135
C     A LENGTH IS ASSUMED FOR THE PURE COMPONENT CONDENSATION           REFC0136
C                                                                       REFC0137
      HALF=(UPLT+LOWLT)/2.0                                             REFC0138
      ASSL=HALF                                                         REFC0139
      P = RLG                                                           REFC0140
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  3   WL(1)=P*WV(1)                                                     REFC0141
      WTC(1)=0.0                                                        REFC0142
      WT(1)=WV(1)+WL(1)                                                 REFC0143
      X(1)=WV(1)/WT(1)                                                  REFC0144
      QY(1)=0.0                                                         REFC0145
      ITER=0                                                            REFC0146
      T(1)=T1                                                           REFC0147
      LENGTH(1)=0.0                                                     REFC0148
      WVEND=(1.0-P)*WV(1)                                               REFC0149
C                                                                       REFC0150
C                                                                       REFC0151
C                                                                       REFC0152
      DO 4 JJ=1,MAXIT                                                   REFC0153
      ITER=ITER+1                                                       REFC0154
C     ANY VALUE OF INCY CAN BE CHOSEN DEPENDING ON THE ACCURACY         REFC0155
C     DESIRED.                                                          REFC0156
C                                                                       REFC0157
      IF(ITER.GT.50) INCY=0.01                                          REFC0158
C     THIS STATEMENT GIVES GREATER ACCURACY TOWARDS THE TOP             REFC0159
C     OF THE TUBE WHERE THE LIQUID RATE IS GOING TO ZERO.               REFC0160
C                                                                       REFC0161
       IF(JJ.NE.1) GO TO 32                                             REFC0162
       DELX=0.0                                                         REFC0163
       CALL FORNEW                                                      REFC0164
       CALL HCOEF                                                       REFC0165
       CALL OVCOEF                                                      REFC0166
       FACTOR(JJ)=1.0/(UO(JJ)*(TSAT-T(JJ)))                             REFC0167
       DELQT(1)=0.0                                                     REFC0168
       GO TO 4                                                          REFC0169
 32   LENGTH(JJ)=LENGTH(JJ-1)+INCY                                      REFC0170
C                                                                       REFC0171
C                                                                       REFC0172
      TWALL(JJ) = TSAT - (UO(JJ-1)/HY(JJ-1)) * (TSAT-T(JJ-1))           REFC0173
C                                                                       REFC0174
C     ASSUMING THAT THE VALUES OBTAINED FOR THE PREVIOUS INTERVAL       REFC0175
C     HOLDS GOOD OVER THE SAMLL INCREMENT                               REFC0176
C                                                                       REFC0177
      DELQT(JJ)=PI*DI*INCY*UO(JJ-1)*(TSAT-T(JJ-1))                      REFC0178
      WTC(JJ)=DELQT(JJ)/ALAMDA                                          REFC0179
C     ONLY THE LATENT HEAT HAS BEEN CONSIDERED FOR PURE COMPONENT CASE  REFC0180
C                                                                       REFC0181
      WV(JJ)=WV(JJ-1)-WTC(JJ)                                           REFC0182
      WL(JJ)=WL(JJ-1)-WTC(JJ)                                           REFC0183
      IF(WL(JJ).LT.0.0) WL(JJ)=0.0                                      REFC0184
      WT(JJ)=WL(JJ)+WV(JJ)                                              REFC0185
      X(JJ)=WV(JJ)/WT(JJ)                                               REFC0186
      DELX=X(JJ)-X(JJ-1)                                                REFC0187
      CALL FORNEW                                                       REFC0188
      IF(WL(JJ).EQ.0.0) GO TO 5                                         REFC0189
      CALL HCOEF                                                        REFC0190
  5   CALL OVCOEF                                                       REFC0191
      QY(JJ)=QY(JJ-1)+DELQT(JJ)                                         REFC0192
C     IF COUNTER CURRENT FLOW THE SIGN SHOULD BE CHANGED TO NEGATIVE    REFC0193
      T(JJ)=T(JJ-1)-(DELQT(JJ)/(CPC*WCOOL))                             REFC0194
      FACTOR(JJ)=1.0/(UO(JJ)*(TSAT-T(JJ)))                              REFC0195
      IF((WV(JJ)-WVEND).LE.0.7) GO TO 6                                 REFC0196
C                                                                       REFC0197
      IF(WL(JJ).EQ.0.0) GO TO 6                                         REFC0198
      ERR=ABS(QT-QY(JJ))                                                REFC0199
      IF(ERR.LE.0.1) GO TO 6                                            REFC0200
  4   CONTINUE                                                          REFC0201
  6   ERRL=ABS(ASSL-LENGTH(JJ))                                         REFC0202
      IF(ERRL.LE.0.1) GO TO 7                                           REFC0203
      CALL CONVER                                                       REFC0204
C                                                                       REFC0205
C     AN INTERVAL HALVING TYPE OF CONVERGENCE IS USED                   REFC0206
C                                                                       REFC0207
      GO TO 3                                                           REFC0208
  7   NTUBES=QTOTAL/QT                                                  REFC0209
      IF(LUNITS.EQ.1) CALL CUNIT                                        REFC0210
```

```
      CALL RESULT
      WRITE(6,8)
 8    FORMAT(1H1)
      STOP
C
C
C     THE FOLLOWING CALCULATIONS ARE FOR A MULTICOMPONENT CASE
   2  CONTINUE
      P = RLG
      WL(1)=P*WV(1)
      WTC(1)=0.0
      WT(1)=WL(1)+WV(1)
      X(1)=WV(1)/WT(1)
C
C
C     THE WEIGHT FRACTIONS OF THE VAPOR AT EACH TEMPERATURE
C     WAS PRECALCULATED
C
C
      DO 9 JM=2,ITER
      WV(JM)=WV(1)*WTFRVA(JM)
      WTC(JM)=WV(JM-1)-WV(JM)
      WL(JM)=WL(JM-1)-WTC(JM)
      IF(WL(JM).LT.0.0) WL(JM)=0.0
      WT(JM)=WV(JM)+WL(JM)
      X(JM)=WV(JM)/WT(JM)
   9  CONTINUE
C
C
      QT=WV(1)*(ENTHF(1)-ENTHF(ITER))/(AVMWT)
      T(1)=T1
      T(ITER)=T2
C
      WCOOL=QT/(CPC*ABS(T(ITER)-T(1)))
      ASSL = 50.0
 56   LENGTH(1)=0.0
      QY(1)=0.0
C
C
      DO 10 JJ=1,ITER
      CALL HSVCOF
C
C
      IF(JJ.NE.1) GO TO 22
       DELX=0.0
       CALL FORNEW
       CALL HCOEF
       CALL OVCOEF
       DELQSV(JJ)=0.0
       DELQT(JJ)=0.0
       HSVAV(JJ)=0.0
       Z(JJ)=0.0
       FACTOR(JJ)=(1.0/(VAPTEM(JJ)-T(JJ)))
       GO TO 10
C
 22   DELQSV(JJ)=((WV(JJ)+WV(JJ-1))/2.0)*(ENTHV(JJ-1)-ENTHV(JJ))
      QY(JJ)=WV(1)*(ENTHF(1)-ENTHF(JJ))/AVMWT
      DELQT(JJ)=QY(JJ)-QY(JJ-1)
      TWALL(JJ) = VAPTEM(JJ) - (UO(JJ-1)/HY(JJ-1)) * (VAPTEM(JJ)
     1             - T(JJ-1))
C     IF COUNTER CURRENT SIGN SHOULD BE CHANGED TO NEGATIVE
      T(JJ)=T(JJ-1)-(DELQT(JJ)/(CPC*WCOOL))
      Z(JJ)=DELQSV(JJ)/DELQT(JJ)
      HSVAV(JJ)=(HSV(JJ)+HSV(JJ-1))/2.0
C
C
      UPLT=50.0
      LOWLT=0.0
      HALF=(LOWLT+UPLT)/2.0
      INCY=HALF
```

```
 11   DELX=X(JJ)-X(JJ-1)                                                REFC0281
      LENGTH(JJ)=LENGTH(JJ-1)+INCY                                      REFC0282
      CALL FORNEW                                                       REFC0283
      IF(WL(JJ).EQ.0.0) GO TO 12                                        REFC0284
      CALL HCOEF                                                        REFC0285
 12   CALL OVCOEF                                                       REFC0286
      FACTOR(JJ)=(1.0+(Z(JJ)*UO(JJ)/HSVAV(JJ)))/(UO(JJ)*(VAPTEM(JJ)-   REFC0287
     *T(JJ)))                                                           REFC0288
      CALDEL=FACTOR(JJ)*(DELQT(JJ)/(PI*DI))                             REFC0289
      ERROR=ABS(INCY-CALDEL)                                            REFC0290
      IF(ERROR.LE.0.1) GO TO 101                                        REFC0291
      CALL NEWT                                                         REFC0292
      GO TO 11                                                          REFC0293
 101   IF(JJ.EQ.ITER) GO TO 102                                         REFC0294
 10   CONTINUE                                                          REFC0295
 102  IF(ABS(LENGTH(JJ)-ASSL).LE.0.1) GO TO 55                          REFC0296
       ASSL = LENGTH(JJ)                                                REFC0297
      GO TO 56                                                          REFC0298
  55  NTUBES=QTOTAL/QT                                                  REFC0299
      IF(LUNITS.EQ.1) CALL CUNIT                                        REFC0300
      CALL RESULT                                                       REFC0301
      WRITE(6,14)                                                       REFC0302
 14   FORMAT(1H1)                                                       REFC0303
      STOP                                                              REFC0304
      END                                                               REFC0305
C                                                                       REFC0306
C                                                                       REFC0307
C                                                                       REFC0308
C                                                                       REFC0309
C                                                                       REFC0310
C     SUBROUTINE  READ1 READS THE  INPUT  PARAMETERS.                   REFC0311
C                                                                       REFC0312
C                                                                       REFC0313
C                                                                       REFC0314
      SUBROUTINE READ1                                                  REFC0315
      REAL INCY,LOWLT                                                   REFC0316
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)                REFC0317
      COMMON/C2/AMUV,BETA,PI,FO(99),TW(99),QY(101),X(99),WT(99),HN(99)  REFC0318
      COMMON/C3/AMUL,AKL,HY(99),CPL,ASSL,WV(99),T(99),Q(99),TWALL(99)   REFC0319
      COMMON/C4/T1,T2,TSAT,D,QT,ALAMDA,HW,WC,P,WL(99),DELX              REFC0320
      COMMON/C5/NA,PR,UO(99),AKW,WALLTH,RFI,RFO,G,COMP(99),AVMWT,CONV,ODREFC0321
      COMMON/C6/V,AREA,HC(99),COMPS(10,3),CPG,CPC,AKV                   REFC0322
      COMMON/C7/ITER,M,VAPTEM(99),ENTHV(99),ENTHF(99),WTFRVA(99)        REFC0323
      COMMON/C8/DELQSV(99),DELQT(99),RECNO(99),WTC(99),FACTOR(101)      REFC0324
      COMMON/C9/HSV(99),HSVAV(99),FDF(99),FDM(99),FDA(99),AF(99),WCOOL  REFC0325
      COMMON/C10/NCOMPS,LENGTH(125),CALDEL,INCY,MAXIT,LENT(125)         REFC0326
      COMMON/C11/LOWLT,UPLT,HALF,AMOLFR(20),QTOTAL,NTUBES,LUNITS        REFC0327
C                                                                       REFC0328
      READ(5,15) D,OD,PI,RLG,SIGMA,HW,T1,T2,CONV                        REFC0329
  15  FORMAT(9F8.0)                                                     REFC0330
      READ(5,16) CPC,PR,AKW,WALLTH,RFI,RFO,G                            REFC0331
  16  FORMAT(F4.0,5F8.0,E15.8)                                          REFC0332
      READ(5,17) AMUV,AMUL,CPL,AKL,ALAMDA,RHOG,RHOL                     REFC0333
  17  FORMAT(7F10.0)                                                    REFC0334
      IF(M.EQ.0) READ(5,18) TSAT,INCY,MAXIT                             REFC0335
  18  FORMAT(2F10.0,I3)                                                 REFC0336
      READ(5,19) UPLT,LOWLT                                             REFC0337
  19  FORMAT(2F10.0)                                                    REFC0338
      IF(M.EQ.0) READ(5,20) (COMP(I),I=1,3)                             REFC0339
  20  FORMAT(3A4)                                                       REFC0340
      IF(M.EQ.1) READ(5,21) NCOMPS,ITER,AVMWT,CPG,AKV                   REFC0341
  21  FORMAT(2I3,3F10.0)                                                REFC0342
      IF(M.EQ.1) READ(5,22) (VAPTEM(I),WTFRVA(I),ENTHV(I),              REFC0343
     *ENTHF(I),I=1,ITER)                                                REFC0344
  22  FORMAT(4F10.0)                                                    REFC0345
      IF(M.EQ.1) READ(5,23)  ((COMPS(I,J),J=1,3),I=1,NCOMPS),(AMOLFR(K),REFC0346
     *K=1,NCOMPS)                                                       REFC0347
  23  FORMAT(3A4,F5.0)                                                  REFC0348
      READ(5,24) QTOTAL                                                 REFC0349
  24  FORMAT(E20.10)                                                    REFC0350
```

```
C
      RETURN
      END
C
C
C
C     SUBROUTINE FLVEL DETERMINES THE FLOODING VELOCITY
C
C     USING DIEHL KOPPANY CORRELATION
C
C
      SUBROUTINE FLVEL
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)
      COMMON/C4/T1,T2,TSAT,D,QT,ALAMDA,HW,WC,P,WL(99),DELX
C
C
      SIGMA1=SIGMA/80.0
      R=D/SIGMA1
      F1=1.0
      IF(R.LT.1.0) F1=R**0.4
      F2=1.0/(RLG**0.25)
      FUNC=F1*F2*SQRT(SIGMA/RHOG)
      VF=0.71*(FUNC**1.15)
      IF(FUNC.GT.10.0) VF=FUNC
      RETURN
      END
C
C
C
C     SUBROUTINE HCOEF CALCULATES THE LOCAL CONDENSING
C     HEAT TRANSFER COEFFICIENT
C
C
C     HT. TRANSFER COEFFICIENT USING MODIFIED COLBURN EQUATION
C     AND NUSSELT EQUATION IS COMPUTED. THE LARGER VALUE IS USED
C     FOR DESIGN PURPOSES.
C
C
C
      SUBROUTINE HCOEF
      REAL LENGTH
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)
      COMMON/C2/AMUV,BETA,PI,FO(99),TW(99),QY(101),X(99),WT(99),HN(99)
      COMMON/C3/AMUL,AKL,HY(99),CPL,ASSL,WV(99),T(99),Q(99),TWALL(99)
      COMMON/C4/T1,T2,TSAT,D,QT,ALAMDA,HW,WC,P,WL(99),DELX
      COMMON/C5/NA,PR,UO(99),AKW,WALLTH,RFI,RFO,G,COMP(99),AVMWT,CONV,OD
      COMMON/C6/V,AREA,HC(99),COMPS(10,3),CPG,CPC,AKV
      COMMON/C7/ITER,M,VAPTEM(99),ENTHV(99),ENTHF(99),WTFRVA(99)
      COMMON/C9/HSV(99),HSVAV(99),FDF(99),FDM(99),FDA(99),AF(99),WCOOL
      COMMON/C10/NCOMPS,LENGTH(125),CALDEL,INCY,MAXIT,LENT(125)
C
      PRL=(CPL*AMUL)/(AKL)
      HC(JJ)=(0.036*(PRL**0.65)*AKL*SQRT(RHOL*FO(JJ)))/AMUL
      HY(JJ) = HC(JJ)
      IF(JJ.EQ.1) GO TO 6
      IF(M.EQ.1) TSAT=VAPTEM(JJ)
      HN(JJ)=((AKL**3*RHOL*(RHOL-RHOG)*G*ALAMDA)/((AMUL*4)*(TSAT-TWALL(J
     1          J))*ABS(ASSL-LENGTH(JJ))))**0.25
C
C
C
C
      IF(HN(JJ).GT.HC(JJ)) HY(JJ)=HN(JJ)
C
C
C
    6 RETURN
      END
C
C
```

```
      SUBROUTINE CUNIT                                                  REFC0421
      REAL LENGTH                                                       REFC0422
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)                REFC0423
      COMMON/C2/AMUV,BETA,PI,FO(99),TW(99),QY(101),X(99),WT(99),HN(99)  REFC0424
      COMMON/C3/AMUL,AKL,HY(99),CPL,ASSL,WV(99),T(99),Q(99),TWALL(99)   REFC0425
      COMMON/C4/T1,T2,TSAT,D,QT,ALAMDA,HW,WC,P,WL(99),DELX              REFC0426
      COMMON/C5/NA,PR,UO(99),AKW,WALLTH,RFI,RFO,G,COMP(99),AVMWT,CONV,ODREFC0427
      COMMON/C6/V,AREA,HC(99),COMPS(10,3),CPG,CPC,AKV                   REFC0428
      COMMON/C7/ITER,M,VAPTEM(99),ENTHV(99),ENTHF(99),WTFRVA(99)        REFC0429
      COMMON/C8/DELQSV(99),DELQT(99),RECNO(99),WTC(99),FACTOR(101)      REFC0430
      COMMON/C9/HSV(99),HSVAV(99),FDF(99),FDM(99),FDA(99),AF(99),WCOOL  REFC0431
      COMMON/C10/NCOMPS,LENGTH(125),CALDEL,INCY,MAXIT,LENT(125)         REFC0432
      COMMON/C11/LOWLT,UPLT,HALF,AMOLFR(20),QTOTAL,NTUBES,LUNITS        REFC0433
C                                                                       REFC0434
C                                                                       REFC0435
       TSAT = (TSAT-32.0) /1.8 + 273.16                                 REFC0436
       DO 40 L=1,ITER                                                   REFC0437
       IF(M.EQ.0) VAPTEM(L) = TSAT                                      REFC0438
       IF(M.EQ.0) GO TO 41                                              REFC0439
       VAPTEM(L) = (VAPTEM(L) - 32.0)/1.8 + 273.16                      REFC0440
       CPG = CPG * 4.186                                                REFC0441
       AKV = AKV * 1.7307                                               REFC0442
 41    T(L) = (T(L) - 32.0)/1.8 + 273.16                                REFC0443
       LENGTH(L) = LENGTH(L) * 0.3048                                   REFC0444
       WV(L) = WV(L) * 0.45359                                          REFC0445
       WL(L) = WL(L) * 0.45359                                          REFC0446
       WTC(L) = WTC(L) * 0.45359                                        REFC0447
       WT(L) = WT(L) * 0.45359                                          REFC0448
       IF(L.EQ.ITER) GO TO 42                                           REFC0449
       HY(L) = HY(L) * 5.6782                                           REFC0450
 42    UO(L) = UO(L) * 5.6782                                           REFC0451
       QY(L) = QY(L) * 0.293076                                         REFC0452
       DELQT(L) = DELQT(L) * 0.293076                                   REFC0453
       AF(L) = AF(L) * G * 47.88                                        REFC0454
       FDF(L) = FDF(L) * G * 47.88                                      REFC0455
       FDM(L) = FDM(L) * G * 47.88                                      REFC0456
       FDA(L) = FDA(L) * G * 47.88                                      REFC0457
       FO(L) = FO(L) * G * 47.88                                        REFC0458
       IF(M.EQ.0) GO TO 40                                              REFC0459
       HSV(L) = HSV(L) * 5.6782                                         REFC0460
       HSVAV(L) = HSVAV(L) * 5.6782                                     REFC0461
       DELQSV(L) = DELQSV(L) * 0.293076                                 REFC0462
 40    CONTINUE                                                         REFC0463
C                                                                       REFC0464
       VF = VF * 0.3048                                                 REFC0465
       V = V * 0.3048                                                   REFC0466
       AREA = AREA * 0.0929                                             REFC0467
       QT = QT * 0.293076                                               REFC0468
       QTOTAL = QTOTAL * 0.290376                                       REFC0469
       WCOOL = WCOOL * 0.45359                                          REFC0470
       PR = PR * 6.895 E+03                                             REFC0471
       CPL = CPL * 4.186                                                REFC0472
       CPC = CPC * 4.186                                                REFC0473
       ALAMDA = ALAMDA * 2.3256                                         REFC0474
       RHOL = RHOL * 16.0                                               REFC0475
       RHOG = RHOG * 16.0                                               REFC0476
       AMUL = AMUL * 4.1338 E-04                                        REFC0477
       AMUV = AMUV * 4.1338 E-04                                        REFC0478
       T1 = (T1 - 32.0 ) /1.8 + 273.16                                  REFC0479
       T2 = (T2 - 32.0 ) /1.8 + 273.16                                  REFC0480
       AKL = AKL * 1.7307                                               REFC0481
       AKW = AKW * 1.7307                                               REFC0482
       RFI = RFI * 0.17611                                              REFC0483
       RFO = RFO * 0.17611                                              REFC0484
       HW = HW * 5.6782                                                 REFC0485
       OD = OD * 0.0254                                                 REFC0486
       WALLTH = WALLTH * 0.0254                                         REFC0487
       RETURN                                                           REFC0488
       END                                                              REFC0489
C                                                                       REFC0490
```

```
C                                                                       REFC0491
C     SUBROUTINE FORNEW CALCULATES THE TOTAL FORCE                      REFC0492
C                                                                       REFC0493
C     ACTING ON THE CONDENSATE OF DIFEERENTIAL  THIKNESS                REFC0494
C                                                                       REFC0495
C     DELTA Z .  FO=FA+FM-FF                                            REFC0496
C                                                                       REFC0497
C                                                                       REFC0498
C                                                                       REFC0499
C     THE CORRELATIONS USED ARE THAT OF SOLIMAN ET.AL                   REFC0500
C                                                                       REFC0501
C                                                                       REFC0502
      SUBROUTINE FORNEW                                                 REFC0503
      REAL INCY                                                         REFC0504
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)                REFC0505
      COMMON/C2/AMUV,BETA,PI,FO(99),TW(99),QY(101),X(99),WT(99),HN(99)  REFC0506
      COMMON/C3/AMUL,AKL,HY(99),CPL,ASSL,WV(99),T(99),Q(99),TWALL(99)   REFC0507
      COMMON/C4/T1,T2,TSAT,D,QT,ALAMDA,HW,WC,P,WL(99),DELX              REFC0508
      COMMON/C5/NA,PR,UO(99),AKW,WALLTH,RFI,RFO,G,COMP(99),AVMWT,CONV,ODREFC0509
      COMMON/C6/V,AREA,HC(99),COMPS(10,3),CPG,CPC,AKV                   REFC0510
      COMMON/C7/ITER,M,VAPTEM(99),ENTHV(99),ENTHF(99),WTFRVA(99)        REFC0511
      COMMON/C8/DELQSV(99),DELQT(99),RECNO(99),WTC(99),FACTOR(101)      REFC0512
      COMMON/C9/HSV(99),HSVAV(99),FDF(99),FDM(99),FDA(99),AF(99),WCOOL  REFC0513
      COMMON/C10/NCOMPS,LENGTH(125),CALDEL,INCY,MAXIT,LENT(125)         REFC0514
C                                                                       REFC0515
C                                                                       REFC0516
C                                                                       REFC0517
C                                                                       REFC0518
      RET=(4.0*WT(JJ)/(PI*DI*AMUV))                                     REFC0519
C                                                                       REFC0520
      AF(JJ)=(8.0*(WT(JJ)**2)/(PI**2*RHOG*(DI**4)))                     REFC0521
C                                                                       REFC0522
C                                                                       REFC0523
      RECNO(JJ)=(4.0*WL(JJ)/(PI*DI*AMUL))                               REFC0524
      IF(RECNO(JJ).LE.240.0) BETA = 2.0                                 REFC0525
      IF(RECNO(JJ).GT.240.0) BETA=1.25                                  REFC0526
      FF=(AF(JJ)*0.045/(RET**0.2))*(X(JJ)**1.8+5.7*((AMUL/AMUV)**0.0523)REFC0527
     1    *((1.0-X(JJ))**0.47)*(X(JJ)**1.33)*((RHOG/RHOL)**0.261)+      REFC0528
     2     8.11*((AMUL/AMUV)**0.105)*((1.0-X(JJ))**0.94)*(X(JJ)**0.86)* REFC0529
     3     ((RHOG/RHOL)**0.522))                                        REFC0530
C                                                                       REFC0531
C                                                                       REFC0532
C                                                                       REFC0533
      IF (JJ.EQ.1) GO TO 36                                             REFC0534
      FMO=AF(JJ)*0.5*(DI*DELX/INCY)*(2.0*(1.0-X(JJ))*((RHOG/RHOL)**0.67)REFC0535
     1   +(1.0/X(JJ)-3.0+2.0*X(JJ))*((RHOG/RHOL)**1.33)+                REFC0536
     2    (2.0*X(JJ)-1.0-BETA*X(JJ))*(RHOG/RHOL)**0.33+                 REFC0537
     3    (2.0*BETA-BETA/X(JJ)-BETA*X(JJ))*((RHOG/RHOL)**1.67)+         REFC0538
     4    2.0*(1.0-X(JJ)-BETA+BETA*X(JJ))*(RHOG/RHOL))                  REFC0539
         FM=-FMO                                                        REFC0540
C                                                                       REFC0541
      GO TO 37                                                          REFC0542
   36 FM=0.0                                                            REFC0543
C                                                                       REFC0544
C                                                                       REFC0545
C                                                                       REFC0546
   37 FRT=(16.0*(WT(JJ)**2))/((PI**2)*(DI**5)*G*(RHOL-RHOG)*RHOG)       REFC0547
C                                                                       REFC0548
C                                                                       REFC0549
      FA=(AF(JJ)*0.5/FRT)*(1.0-(1.0 /(1.0+((1.0-X(JJ))/X(JJ))*          REFC0550
     1     ((RHOG/RHOL)**0.67))))                                       REFC0551
C                                                                       REFC0552
C                                                                       REFC0553
      FDM(JJ)=FM                                                        REFC0554
      FDF(JJ)=FF                                                        REFC0555
      FDA(JJ)=FA                                                        REFC0556
      FO(JJ)=FA+FM-FF                                                   REFC0557
      IF (FO(JJ).LT.0.0) FO(JJ)=0.0                                     REFC0558
C                                                                       REFC0559
C                                                                       REFC0560
```

```
      RETURN
      END
C     SUBROUTINE HSVCOF COMPUTES THE VAP.HT. TRANSFER COEFFICIENT
C
      SUBROUTINE HSVCOF
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)
      COMMON/C2/AMUV,BETA,PI,FO(99),TW(99),QY(101),X(99),WT(99),HN(99)
      COMMON/C3/AMUL,AKL,HY(99),CPL,ASSL,WV(99),T(99),Q(99),TWALL(99)
      COMMON/C6/V,AREA,HC(99),COMPS(10,3),CPG,CPC,AKV
      COMMON/C9/HSV(99),HSVAV(99),FDF(99),FDM(99),FDA(99),AF(99),WCOOL
      PRL=((CPG*AMUV)/AKV)**0.33
      SEDFAC=1.0
C     THE SEIDER FACTOR IS TAKEN AS ONE
      HSV(JJ)=0.023*(AKV/DI)*(PRL)*((DI*WV(JJ))/(AREA*AMUV))**0.8
     1*SEDFAC
C
C
      RETURN
      END
C
C
C     SUBROUTINE OVCOEF COMPUTES THE OVERALL HT. TRANSFER
C     COEFFICIENT BETWEEN THE INTERFACE AND THE COOLANT FLOW
C
C
      SUBROUTINE OVCOEF
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)
      COMMON/C2/AMUV,BETA,PI,FO(99),TW(99),QY(101),X(99),WT(99),HN(99)
      COMMON/C3/AMUL,AKL,HY(99),CPL,ASSL,WV(99),T(99),Q(99),TWALL(99)
      COMMON/C4/T1,T2,TSAT,D,QT,ALAMDA,HW,WC,P,WL(99),DELX
      COMMON/C5/NA,PR,UO(99),AKW,WALLTH,RFI,RFO,G,COMP(99),AVMWT,CONV,OD
      COMMON/C6/V,AREA,HC(99),COMPS(10,3),CPG,CPC,AKV
      COMMON/C7/ITER,M,VAPTEM(99),ENTHV(99),ENTHF(99),WTFRVA(99)
      COMMON/C8/DELQSV(99),DELQT(99),RECNO(99),WTC(99),FACTOR(101)
      COMMON/C9/HSV(99),HSVAV(99),FDF(99),FDM(99),FDA(99),AF(99),WCOOL
      COMMON/C10/NCOMPS,LENGTH(125),CALDEL,INCY,MAXIT,LENT(125)
C
C
      IF(WL(JJ).EQ.0.0) GO TO 38
      FAC=(1.0/HY(JJ))
   38 IF(WL(JJ).EQ.0.0) FAC=0.0
C
      UO1=FAC+RFI+(WALLTH*D)/(AKW*OD*12.0)+RFO*D/OD+D/(OD*HW)
      UO(JJ)=1.0/UO1
C
C
      RETURN
      END
C
C
C
      SUBROUTINE NEWT
      REAL INCY,LOWLT
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)
      COMMON/C2/AMUV,BETA,PI,FO(99),TW(99),QY(101),X(99),WT(99),HN(99)
      COMMON/C3/AMUL,AKL,HY(99),CPL,ASSL,WV(99),T(99),Q(99),TWALL(99)
      COMMON/C4/T1,T2,TSAT,D,QT,ALAMDA,HW,WC,P,WL(99),DELX
      COMMON/C5/NA,PR,UO(99),AKW,WALLTH,RFI,RFO,G,COMP(99),AVMWT,CONV,OD
      COMMON/C6/V,AREA,HC(99),COMPS(10,3),CPG,CPC,AKV
      COMMON/C7/ITER,M,VAPTEM(99),ENTHV(99),ENTHF(99),WTFRVA(99)
      COMMON/C8/DELQSV(99),DELQT(99),RECNO(99),WTC(99),FACTOR(101)
      COMMON/C9/HSV(99),HSVAV(99),FDF(99),FDM(99),FDA(99),AF(99),WCOOL
      COMMON/C10/NCOMPS,LENGTH(125),CALDEL,INCY,MAXIT,LENT(125)
      COMMON/C11/LOWLT,UPLT,HALF,AMOLFR(20),QTOTAL,NTUBES,LUNITS
C
C
      IF(CALDEL.GT.HALF) LOWLT=HALF
      IF(CALDEL.LT.HALF) UPLT=HALF
      HALF=(LOWLT+UPLT)/2.0
      INCY=HALF
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      RETURN                                                            REFC0631
      END                                                               REFC0632
C                                                                       REFC0633
      SUBROUTINE CONVER                                                 REFC0634
      REAL LENGTH                                                       REFC0635
      REAL INCY,LOWLT                                                   REFC0636
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)                REFC0637
      COMMON/C2/AMUV,BETA,PI,FO(99),TW(99),QY(101),X(99),WT(99),HN(99)  REFC0638
      COMMON/C3/AMUL,AKL,HY(99),CPL,ASSL,WV(99),T(99),Q(99),TWALL(99)   REFC0639
      COMMON/C4/T1,T2,TSAT,D,QT,ALAMDA,HW,WC,P,WL(99),DELX              REFC0640
      COMMON/C5/NA,PR,UO(99),AKW,WALLTH,RFI,RFO,G,COMP(99),AVMWT,CONV,ODREFC0641
      COMMON/C6/V,AREA,HC(99),COMPS(10,3),CPG,CPC,AKV                   REFC0642
      COMMON/C7/ITER,M,VAPTEM(99),ENTHV(99),ENTHF(99),WTFRVA(99)        REFC0643
      COMMON/C8/DELQSV(99),DELQT(99),RECNO(99),WTC(99),FACTOR(101)      REFC0644
      COMMON/C9/HSV(99),HSVAV(99),FDF(99),FDM(99),FDA(99),AF(99),WCOOL  REFC0645
      COMMON/C10/NCOMPS,LENGTH(125),CALDEL,INCY,MAXIT,LENT(125)         REFC0646
      COMMON/C11/LOWLT,UPLT,HALF,AMOLFR(20),QTOTAL,NTUBES,LUNITS        REFC0647
C                                                                       REFC0648
C                                                                       REFC0649
      IF(LENGTH(JJ).GT.HALF) LOWLT=HALF                                 REFC0650
      IF(LENGTH(JJ).LT.HALF) UPLT=HALF                                  REFC0651
      HALF=(LOWLT+UPLT)/2.0                                             REFC0652
      ASSL=HALF                                                         REFC0653
      RETURN                                                            REFC0654
      END                                                               REFC0655
C                                                                       REFC0656
      SUBROUTINE RESULT                                                 REFC0657
      REAL LENGTH                                                       REFC0658
      COMMON/C1/DI,SIGMA,RLG,RHOG,RHOL,VF,JJ,L,ERR,Z(99)                REFC0659
      COMMON/C2/AMUV,BETA,PI,FO(99),TW(99),QY(101),X(99),WT(99),HN(99)  REFC0660
      COMMON/C3/AMUL,AKL,HY(99),CPL,ASSL,WV(99),T(99),Q(99),TWALL(99)   REFC0661
      COMMON/C4/T1,T2,TSAT,D,QT,ALAMDA,HW,WC,P,WL(99),DELX              REFC0662
      COMMON/C5/NA,PR,UO(99),AKW,WALLTH,RFI,RFO,G,COMP(99),AVMWT,CONV,ODREFC0663
      COMMON/C6/V,AREA,HC(99),COMPS(10,3),CPG,CPC,AKV                   REFC0664
      COMMON/C7/ITER,M,VAPTEM(99),ENTHV(99),ENTHF(99),WTFRVA(99)        REFC0665
      COMMON/C8/DELQSV(99),DELQT(99),RECNO(99),WTC(99),FACTOR(101)      REFC0666
      COMMON/C9/HSV(99),HSVAV(99),FDF(99),FDM(99),FDA(99),AF(99),WCOOL  REFC0667
      COMMON/C10/NCOMPS,LENGTH(125),CALDEL,INCY,MAXIT,LENT(125)         REFC0668
      COMMON/C11/LOWLT,UPLT,HALF,AMOLFR(20),QTOTAL,NTUBES,LUNITS        REFC0669
C                                                                       REFC0670
      IF(M.EQ.0) WRITE(6,25)                                            REFC0671
      IF(M.EQ.1) WRITE(6,26)                                            REFC0672
   25 FORMAT(1H1,//////46X,39H***** PURE COMPONENT CONDENSATION *****// REFC0673
     1        46X,28H***** IN A REFLUX CONDENSER.,6X,5H*****)           REFC0674
   26 FORMAT(1H1,//////46X,40H***** MULTI COMPONENT CONDENSATION *****//REFC0675
     1    46X,28H***** IN A REFLUX CONDENSER.,6X,5H*****)               REFC0676
C                                                                       REFC0677
C                                                                       REFC0678
C                                                                       REFC0679
      IF(M.EQ.0) WRITE(6,27) (COMP(I),I=1,3)                            REFC0680
   27 FORMAT(////46X,19HCOMPONENT----------,3A4)                        REFC0681
C                                                                       REFC0682
      IF(M.EQ.1) WRITE(6,28)                                            REFC0683
   28 FORMAT(/////10X,10HCOMPONENTS//)                                  REFC0684
C                                                                       REFC0685
C                                                                       REFC0686
      IF(M.EQ.1) WRITE(6,29) ((COMPS(I,J),J=1,3),I=1,NCOMPS)            REFC0687
     *,(AMOLFR(K),K=1,NCOMPS)                                           REFC0688
   29 FORMAT(/10X,3A4,5X,F6.3,2X,1H%)                                   REFC0689
C                                                                       REFC0690
C                                                                       REFC0691
      WRITE(6,30)                                                       REFC0692
   30 FORMAT(////10X,10HINPUT DATA)                                     REFC0693
C                                                                       REFC0694
      IF(LUNITS.EQ.1) GO TO 70                                          REFC0695
      IF(M.EQ.0) WRITE(6,31) TSAT                                       REFC0696
   31 FORMAT(///10X,10HSAT. TEMP.,15X,F10.3,2X,5HDEG F)                 REFC0697
C                                                                       REFC0698
      IF(M.EQ.1) WRITE(6,32) VAPTEM(1),VAPTEM(ITER)                     REFC0699
   32 FORMAT(///10X,12HVAP.TEMP. IN,13X,F10.3,2X,5HDEG F//10X,          REFC0700
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     113HVAP.TEMP. OUT,12X,F10.3,2X,5HDEG F)
C
C
      WRITE(6,33) PR,CPC,ALAMDA,RHOL,RHOG,AMUV,AMUL,SIGMA,T1,T2,
     1             AKL,AKW,RFI,RFO,CPL,HW,RLG,OD,WALLTH
C
 33   FORMAT(/10X,8HPRESSURE,17X,F10.3,2X,4HPSIG/10X,13HCOOL.SPEC.HT.
     *,12X,F10.6,2X,12HBTU/LB-DEG.F/10X,14HLAT. HT. COND.,11X,F10.3,2X,
     *7HBTU/LBM/10X,10HLIQ. DENS.,15X,F10.6,2X,6HLB/CFT/10X,
     *10HVAP. DENS.,15X,F10.6,2X,6HLB/CFT/10X,10HVAP. VISC.,15X,
     *F10.6,2X,8HLB/FT-HR/10X,10HLIQ. VISC.,15X,
     *F10.6,2X,8HLB/FT-HR/10X,11HSURF. TENS.,14X,F10.3,2X,9HDYNES/CM./
     *10X,13HCOOL. IN TEMP,12X,F10.3,2X,5HDEG F/10X,14HCOOL. OUT TEMP,
     *11X,F10.3,2X,5HDEG F/10X,17HLIQ. THERM. COND.,8X,F10.6,
     *2X,15HBTU/HR-FT-DEG.F/10X,17HWALL THERM. COND.,8X,F10.6,
     *2X,15HBTU/HR-FT-DEG.F/10X,14HINSIDE FOULING,11X,F10.6,2X,
     *17HHR-SQFT DEG.F/BTU/10X,15HOUTSIDE FOULING,10X,F10.6,2X,
     *17HHR-SQFT DEG.F/BTU/10X,14HLIQ. SPEC. HT.,11X,F10.6,2X,
     *12HBTU/LB-DEG.F/10X,16HCOOL. HT. COEFF.,9X,F10.3,2X,
     *17HBTU/HR-SQFT-DEG.F/10X,
     *14HLIQ. GAS RATIO,11X,F10.3/10X,17HOUT. DIA. OF PIPE,8X,F10.6,
     *2X,6HINCHES/10X,14HWALL THICKNESS,11X,F10.6,2X,6HINCHES     )
      IF(M.EQ.1) WRITE(6,34) AKV,CPG
 34   FORMAT(/10X,17HVAP. THERM. COND.,8X,F10.6,2X,15HBTU/HR-FT-DEG.F/
     *10X,14HVAP. SPEC. HT.,11X,F10.6,2X,12HBTU/LB-DEG.F)
      WRITE(6,35) VF,V,AREA,WV(1),QT,WCOOL
 35   FORMAT(1H1,//////10X,13HFLOODING VEL.,12X,F10.6,2X,7HFT/SEC.//
     *10X,14HOPERATING VEL.,11X,F10.3,2X,6HFT/HR.//10X,21HCROSS SECT. AR
     *EA/TUBE,5X,F10.7,2X,4HSQFT//10X,16HVAP. COND. /TUBE,9X,F10.4,2X,
     *5HLB/HR//10X,14HHEAT DUTY/TUBE,11X,E15.7,2X,6HBTU/HR//10X,
     *17HCOOLANT RATE/TUBE,9X,F10.4,2X,5HLB/HR)
      WRITE(6,39)
C
      DO 40 L=1,ITER
      IF(M.EQ.0) VAPTEM(L)=TSAT
      WRITE(6,41) L,VAPTEM(L),T(L),LENGTH(L),WV(L),WL(L),WTC(L),WT(L)
   40 CONTINUE
      WRITE(6,42)
C
      DO 43 IM=1,ITER
      IF(IM.EQ.ITER) WRITE(6,44) IM,X(IM),RECNO(IM),UO(IM),QY(IM)
     *,DELQT(IM),FACTOR(IM)
      IF(IM.EQ.ITER) GO TO 43
      WRITE(6,45) IM,X(IM),RECNO(IM),HY(IM),UO(IM),QY(IM),DELQT(IM)
     *,FACTOR(IM)
   43 CONTINUE
C
      WRITE(6,46)
C
      DO 47 N=1,ITER
       AF(N) = AF(N) * G
       FDF(N) = FDF(N) * G
       FDM(N) = FDM(N) * G
       FDA(N) = FDA(N) * G
       FO(N) = FO(N) * G
      WRITE(6,48) N,AF(N),FDF(N),FDM(N),FDA(N),FO(N)
   47 CONTINUE
      IF(M.EQ.0) GO TO 49
C
      WRITE(6,50)
      DO 51 J=1,ITER
      WRITE(6,52) J,HSV(J),HSVAV(J),DELQSV(J),Z(J)
   51 CONTINUE
C
C
 39   FORMAT(1H1,//11X,4HITER,3X,14HBULK VAP.TEMP.,3X,13HCOOLANT TEMP.,3
     *X,6HLENGTH,3X,8HVAP.RATE,3X,8HLIQ.RATE,3X,9HCOND.RATE,3X,10HTOTAL
     *RATE/19X,12H(FAHRENHEIT),4X,12H(FAHRENHEIT),4X,6H(FEET),4X,
     * 7H(LB/HR),4X,7H(LB/HR),4X,7H(LB/HR),5X,7H(LB/HR)///)
C
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C                                                                       REFC0771
   41  FORMAT(11X,I3,5X,F8.4,9X,F8.4,6X,F6.3,3X,F8.3,3X,F8.3,4X,F8.3,4X, REFC0772
      *F8.3/)                                                           REFC0773
C                                                                       REFC0774
C                                                                       REFC0775
   42  FORMAT(1H1,//11X,4HITER,3X,7HQUALITY,3X,10HCON.RE.NO.,3X,17HCOND.HREFC0776
      *T.TR.COEFF.,4X,15HOV.HT.TR.COEFF.,4X,9HHT.RECOV.,3X,14HDIFF.HT.RECREFC0777
      *OV.,3X,8HORDINATE/40X,19H(BTU/HR-SQFT-DEG.F),1X,19H(BTU/HR-SQFT-DEREFC0778
      *G.F),4X,8H(BTU/HR),5X,8H(BTU/HR)///)                             REFC0779
   45   FORMAT(11X,I3,3X,F7.5,3X,F10.4,5X,F10.4,10X,F10.4,8X,F10.4,5X,F10REFC0780
      *.4,5X,F9.6/)                                                     REFC0781
   44   FORMAT(11X,I3,3X,F7.5,3X,F10.4,7X,8HINFINITY,10X,F10.4,8X,F10.4,5REFC0782
      *X,F10.4,5X,F9.6/)                                                REFC0783
C                                                                       REFC0784
   46   FORMAT(1H1,//11X,4HITER,3X,12HFORCE CONST.,3X,11HFRICT.FORCE,5X, REFC0785
      * 12HMOMENT.FORCE,4X,11HACCEL.FORCE,6X,11HTOTAL FORCE/17X,        REFC0786
      * 11H(LBF/FT**2),5X,11H(LBF/FT**2),5X,11H(LBF/FT**2),             REFC0787
      * 5X,11H(LBF/FT**2),5X,11H(LBF/FT**2)///)                         REFC0788
   48   FORMAT(11X,I3,3X,E12.6,3X,E12.6,4X,E12.6,4X,E12.6,4X,E13.6/)    REFC0789
C                                                                       REFC0790
C                                                                       REFC0791
   50   FORMAT(1H1,//11X,4HITER,5X,15HGAS FILM COEFF.,8X,18HAV.GAS FILM CREFC0792
      *OEFF.,5X,12HVAP.SEN.LOAD,5X,12HDELQSV/DELQT/17X,19H(BTU/HR-SQFT-DEREFC0793
      *G.F),5X,19H(BTU/HR-SQFT-DEG.F),5X,8H(BTU/HR)///)                 REFC0794
   52   FORMAT(11X,I3,3X,F8.4,17X,F8.4,11X,E12.6,8X,F6.4/)              REFC0795
C                                                                       REFC0796
C                                                                       REFC0797
   49   WRITE(6,53) OD,LENGTH(ITER)                                     REFC0798
   53   FORMAT(///10X,28HDIAMETER OF THE TUBE (14BWG),5X,F10.5,2X,      REFC0799
      *6HINCHES//10X,18HLENGTH OF THE TUBE,5X,F6.2,2X,4HFEET)           REFC0800
C                                                                       REFC0801
C                                                                       REFC0802
        WRITE(6,54) QTOTAL,NTUBES                                       REFC0803
   54   FORMAT(///10X,27HNO.OF TUBES REQD.TO RECOVER,2X,E12.5,2X,       REFC0804
      *6HBTU/HR,5X,I5)                                                  REFC0805
         RETURN                                                         REFC0806
  70   IF(M.EQ.0) WRITE(6,71) TSAT                                      REFC0807
  71   FORMAT(///10X,10HSAT. TEMP.,15X,F10.3,2X,5HDEG K)                REFC0808
C                                                                       REFC0809
       IF(M.EQ.1) WRITE(6,72) VAPTEM(1),VAPTEM(ITER)                    REFC0810
  72   FORMAT(///10X,12HIN VAP.TEMP.,13X,F10.3,2X,5HDEG K//10X,         REFC0811
      113HOUT VAP.TEMP.,12X,F10.3,2X,5HDEG K)                           REFC0812
C                                                                       REFC0813
C                                                                       REFC0814
       WRITE(6,73) PR,CPC,ALAMDA,RHOL,RHOG,AMUV,AMUL,SIGMA,T1,T2,       REFC0815
      1             AKL,AKW,RFI,RFO,CPL,HW,BETA,RLG,OD,WALLTH           REFC0816
C                                                                       REFC0817
  73   FORMAT(/10X,8HPRESSURE,17X,F10.3,2X,4HN/M2/10X,13HCOOL.SPEC.HT.  REFC0818
      *,12X,F10.6,2X,12HKJS/KG-DEG.K/10X,14HLAT. HT. COND.,11X,F10.3,2X, REFC0819
      *7HKJS/KG /10X,10HLIQ. DENS.,15X,F10.6,2X,7HKG/M**3/10X,          REFC0820
      *10HVAP. DENS.,15X,F10.6,2X,7HKG/M**3/10X,10HVAP. VISC.,15X,      REFC0821
      *F10.6,2X,8HKG/M-SEC/10X,10HLIQ. VISC.,15X,                       REFC0822
      *F10.6,2X,8HKG/M-SEC/10X,11HSURF. TENS.,14X,F10.3,2X,9HDYNES/CM./ REFC0823
      *10X,13HCOOL. IN TEMP,12X,F10.3,2X,5HDEG K/10X,14HCOOL. OUT TEMP, REFC0824
      *11X,F10.3,2X,5HDEG K/10X,17HLIQ. THERM. COND.,8X,F10.6,          REFC0825
      *2X,13HWATTS/M-DEG.K/10X,17HWALL THERM. COND.,8X,F10.6,           REFC0826
      *2X,13HWATTS/M-DEG.K/10X,14HINSIDE FOULING,11X,F10.6,2X,          REFC0827
      *16HM**2 DEG.K/WATTS/10X,15HOUTSIDE FOULING,10X,F10.6,2X,         REFC0828
      *16HM**2 DEG.K/WATTS/10X,14HLIQ. SPEC. HT.,11X,F10.6,2X,          REFC0829
      *12HKJS/KG-DEG.K/10X,16HCOOL. HT. COEFF.,9X,F10.3,2X,             REFC0830
      *16HWATTS/M**2-DEG.K/10X,18HDIMENSIONLESS VEL.,7X,F10.3/10X,      REFC0831
      *14HLIQ. GAS RATIO,11X,F10.3/10X,17HOUT. DIA. OF PIPE,8X,F10.6,   REFC0832
      *2X,6HMETERS/10X,14HWALL THICKNESS,11X,F10.6,2X,6HMETERS     )    REFC0833
       IF(M.EQ.1) WRITE(6,74) AKV,CPG                                   REFC0834
  74   FORMAT(/10X,17HVAP. THERM. COND.,8X,F10.6,2X,13HWATTS/M-DEG.K/   REFC0835
      *10X,14HVAP. SPEC. HT.,11X,F10.6,2X,12HKJS/KG-DEG.K)              REFC0836
       WRITE(6,75) VF,V,AREA,WV(1),QT,WCOOL,P                           REFC0837
  75   FORMAT(1H1,/////10X,13HFLOODING VEL.,12X,F10.6,2X,6HM/SEC.//     REFC0838
      *10X,14HOPERATING VEL.,11X,F10.3,2X,5HM/HR.//10X,21HCROSS SECT. AREREFC0839
      *A/TUBE,5X,F10.7,2X,3HSQM//10X,16HVAP. COND. /TUBE,9X,F10.4,2X,   REFC0840
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     *5HKG/HR//10X,14HHEAT DUTY/TUBE,11X,E15.7,2X,5HWATTS//10X,         REFC0841
     *17HCOOLANT RATE/TUBE,9X,F10.4,2X,5HKG/HR//10X,                    REFC0842
     *18HFRACTION CONDENSED,9X,F5.3)                                    REFC0843
      WRITE(6,79)                                                       REFC0844
C                                                                       REFC0845
      DO 80 L=1,ITER                                                    REFC0846
      IF(M.EQ.0) VAPTEM(L)=TSAT                                         REFC0847
      WRITE(6,81) L,VAPTEM(L),T(L),LENGTH(L),WV(L),WL(L),WTC(L),WT(L)   REFC0848
   80 CONTINUE                                                          REFC0849
      WRITE(6,82)                                                       REFC0850
C                                                                       REFC0851
      DO 83 IM=1,ITER                                                   REFC0852
      IF(IM.EQ.ITER) WRITE(6,84) IM,X(IM),RECNO(IM),UO(IM),QY(IM)       REFC0853
     *,DELQT(IM),FACTOR(IM)                                             REFC0854
      IF(IM.EQ.ITER) GO TO 83                                           REFC0855
      WRITE(6,85) IM,X(IM),RECNO(IM),HY(IM),UO(IM),QY(IM),DELQT(IM)     REFC0856
     *,FACTOR(IM)                                                       REFC0857
   83 CONTINUE                                                          REFC0858
C                                                                       REFC0859
      WRITE(6,86)                                                       REFC0860
C                                                                       REFC0861
      DO 87 N=1,ITER                                                    REFC0862
      WRITE(6,88) N,AF(N),FDF(N),FDM(N),FDA(N),FO(N)                    REFC0863
   87 CONTINUE                                                          REFC0864
      IF(M.EQ.0) GO TO 89                                               REFC0865
C                                                                       REFC0866
      WRITE(6,90)                                                       REFC0867
      DO 91 J=1,ITER                                                    REFC0868
      WRITE(6,92) J,HSV(J),HSVAV(J),DELQSV(J),Z(J)                      REFC0869
   91 CONTINUE                                                          REFC0870
C                                                                       REFC0871
C                                                                       REFC0872
 79   FORMAT(1H1,//1X,4HITER,3X,14HBULK VAP.TEMP.,3X,13HCOOLANT TEMP.,3XREFC0873
     *,6HLENGTH,3X,8HVAP.RATE,3X,8HLIQ.RATE,3X,9HCOND.RATE,3X,10HTOTAL RREFC0874
     *ATE/9X,12H(DEG-KELVIN),4X,12H(DEG-KELVIN),4X,6H(METS),4X,         REFC0875
     * 7H(KG/HR),4X,7H(KG/HR),4X,7H(KG/HR),5X,7H(KG/HR)////)            REFC0876
C                                                                       REFC0877
C                                                                       REFC0878
   81 FORMAT(1X,I3,5X,F8.4,9X,F8.4,6X,F6.3,3X,F8.3,3X,F8.3,4X,F8.3,4X,  REFC0879
     *F8.3///)                                                          REFC0880
C                                                                       REFC0881
C                                                                       REFC0882
   82 FORMAT(1H1,//1X,4HITER,3X,7HQUALITY,3X,10HCON.RE.NO.,3X,17HCOND.HTREFC0883
     *.TR.COEFF.,4X,15HOV.HT.TR.COEFF.,4X,9HHT.RECOV.,3X,14HDIFF.HT.RECOREFC0884
     *V.,3X,8HORDINATE/30X,19H(WATTS/ M**2 DEG.K),1X,19H(WATTS/ M**2 DEGREFC0885
     *.K),4X,7H(WATTS),5X,7H(WATTS)////)                                REFC0886
   85  FORMAT(1X,I3,3X,F7.5,3X,F10.4,5X,F10.4,10X,F10.4,8X,F10.4,5X,F10.REFC0887
     *4,5X,F9.6///)                                                     REFC0888
   84  FORMAT(1X,I3,3X,F7.5,3X,F10.4,7X,8HINFINITY,10X,F10.4,8X,F10.4,5XREFC0889
     *,F10.4,5X,F9.6///)                                                REFC0890
C                                                                       REFC0891
   86  FORMAT(1H1,//1X,4HITER,3X,12HFORCE CONST.,3X,11HFRICT.FORCE,5X,  REFC0892
     * 12HMOMENT.FORCE,4X,11HACCEL.FORCE,6X,11HTOTAL FORCE/7X,          REFC0893
     * 13H(NEWTON/M**2),2X,13H(NEWTON/M**2),4X,13H(NEWTON/M**2),        REFC0894
     * 2X,13H(NEWTON/M**2),4X,13H(NEWTON/M**2)////)                     REFC0895
   88  FORMAT(1X,I3,3X,E12.6,3X,E12.6,4X,E12.6,4X,E12.6,4X,E13.6///)    REFC0896
C                                                                       REFC0897
C                                                                       REFC0898
   90  FORMAT(1H1,//1X,4HITER,5X,15HGAS FILM COEFF.,8X,18HAV.GAS FILM COREFC0899
     *EFF.,5X,12HVAP.SEN.LOAD,5X,12HDELQSV/DELQT/7X,19H(WATTS/ M**2 DEG.REFC0900
     *K),5X,19H(WATTS/ M**2 DEG.K),5X,8H(BTU/HR)////)                   REFC0901
   92  FORMAT(1X,I3,3X,F8.4,17X,F8.4,11X,E12.6,8X,F6.4///)              REFC0902
C                                                                       REFC0903
C                                                                       REFC0904
   89  WRITE(6,93) OD,LENGTH(ITER)                                      REFC0905
   93  FORMAT(///10X,28HDIAMETER OF THE TUBE (14BWG),5X,F10.5,2X,       REFC0906
     *6HMETERS//10X,18HLENGTH OF THE TUBE,5X,F6.2,2X,6HMETERS)          REFC0907
C                                                                       REFC0908
C                                                                       REFC0909
       WRITE(6,94) QTOTAL,NTUBES                                        REFC0910
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94    FORMAT(///10X,27HNO.OF TUBES REQD.TO RECOVER,2X,E12.5,2X,          REFC0911
     *5HWATTS,5X,I5)                                                     REFC0912
      RETURN                                                             REFC0913
      END                                                                REFC0914
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VITA

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Master of Science

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