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MANUAL

COMPUTER PROGRAM FOR LIQUID METAL CONDENSING HEAT TRANSFER COEFFICIENTS INSIDE TUBES

by

H. L. Ornstein

prepared for
National Aeronautics and Space Administration
Contract NAS3-2335

Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION

EAST HARTFORD • CONNECTICUT

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FOREWORD

This report is a manual of computer programming for the calculation of liquid-metal condensing-heat-transfer coefficients inside tubes. It was prepared by the Pratt & Whitney Aircraft Division of United Aircraft Corporation for the National Aeronautics and Space Administration, Lewis Research Center, under Contract NAS3-2335, Experimental Investigation of Heat Rejection Problems in Nuclear Space Powerplants.

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I. INTRODUCTION

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Report PWA-2530, NASA CR-54352, Analytical Study of Liquid Metal Condensing Inside Tubes, presents a theoretical analysis that can be used to determine the liquid film thickness and condensing-heat-transfer coefficient at an axial location inside a tube where condensing is occurring. The method also enables determination of the liquid-layer shear-stress distribution, liquid velocity profile, eddy diffusivity for momentum, ratio of eddy diffusivities, and liquid temperature profile. The analysis assumes annular two-phase flow inside circular tubes with no liquid entrainment in the gas core. The final equations derived in that report were programmed in Fortran II for the IBM 7094 digital computer.

This manual presents the following items of that computer program in detail:

1) Program logic,
2) Input format and operational instructions,
3) Printout format,
4) Listing of program statements, and
5) Program flow diagram.

author

II. PROGRAM LOGIC

For a given set of input conditions the program assumes a liquid film thickness and calculates the shear stress distribution and velocity profile within the liquid layer. The program then integrates the velocity profile from the wall to the edge of the film to calculate the liquid flow rate. An iteration routine is used until a film thickness which results in the correct liquid flow rate is found. When the correct liquid flow rate is calculated in this manner, the program calculates the liquid temperature distribution and the condensing-heat-transfer coefficient.

The determination of the correct liquid flow rate is an iterative process which depends upon the value of liquid film thickness and hence upon the liquid fraction R_L*. In order to start the iteration process, the program calculates the liquid fraction R_L based on the Lockhart-Martinelli correlation. It then uses this value of liquid fraction in the following equation as the initial guess to calculate a corresponding value of the dimensionless liquid film thickness **

$$\delta^+ = r_o^+ \left(1 - \sqrt{1 - R_L}\right) \tag{1}$$

The liquid film is then divided into 2N increments whose end points have the following radial locations

$$y^+ = 0, \frac{\delta^+}{2N}, \frac{2\delta^+}{2N}, \frac{3\delta^+}{2N}, \ldots\ldots, \frac{2N\delta^+}{2N}$$

*Nomenclature is defined in Table 1, Appendix C

**Most of the equations presented in this section are derived in Report PWA-2530, NASA CR-54352, Analytical Study of Liquid Metal Condensing Inside Tubes, by H. R. Hunz.

The shear stress is evaluated at each of the 2N + 1 radial locations from the following equation *

$$\frac{\tau}{\tau_o} = \frac{1 + \frac{r_o}{2\,\tau_o}\left[\frac{dP}{d\ell} + \rho_L \frac{g}{g_c}\cos\theta\right]\left[2\left(\frac{y^+}{r_o^+}\right) - \left(\frac{y^+}{r_o^+}\right)^2\right]}{1 - \left(\frac{y^+}{r_o^+}\right)} \qquad (2)$$

where

$$\tau_o = \frac{r_o}{2}\left(\frac{dP}{d\ell}\right)_{friction}$$

and**

$$\frac{dP}{d\ell} = -\left(\frac{dP}{d\ell}\right)_{friction} + \left(\frac{dP}{d\ell}\right)_{momentum} + \left(\frac{dP}{d\ell}\right)_{static\ head}$$

The frictional pressure gradient $\left(\frac{dP}{d\ell}\right)_{friction}$ is a program input item.

The momentum pressure gradient is

$$\left(\frac{dP}{d\ell}\right)_{momentum} = \frac{2}{\pi g_c}\,\frac{W_T}{r_o^3}\,\frac{q_o}{\lambda}\left[2\left(\frac{1-x}{\rho_L R_L} - \frac{x}{\rho_g(1-R_L)}\right) + \left(\frac{(1-x)^2}{\rho_L R_L^2} - \frac{x^2}{\rho_g(1-R_L)^2}\right)\frac{dR_L}{dx}\right]$$

*If τ/τ_o is negative at any radial location, the program will proceed with its normal calculations, but an error printout will occur. See Section V for a discussion of error printouts.

**All of the pressure gradient terms in this equation are actual pressure gradients except for the frictional pressure gradient which is the negative of the actual gradient. The pressure gradient terms in the printout are the negative of the actual gradients in all cases.

where $\frac{dR_L}{dx}$ is calculated using an empirical expression based upon Lockhart and Martinelli's liquid fraction correlation.

The pressure gradient due to static head is

$$\left(\frac{dP}{d\ell}\right)_{static} = -\cos\theta \, \frac{g}{g_c}\left(R_L \, \rho_L + (1-R_L)\,\rho_g \right)$$

The values of $\left(\frac{dP}{d\ell}\right)_{momentum}$ and $\left(\frac{dP}{d\ell}\right)_{static\ head}$ are dependent upon R_L, therefore the iteration procedure is necessary.

$\frac{\epsilon_M}{\nu_L}$ is evaluated at each of the selected y^+ locations from the following equation

$$\frac{\epsilon_M}{\nu_L} = \frac{1}{2}\left[-1 + \sqrt{1 + 4\,\frac{\tau}{\tau_o}\,K^2\,y^{+2}\left(1-e^{-y^+/A^+}\right)^2}\,\right] \qquad (3)$$

where $K = 0.4$ and $A^+ = 26.0$

Generally, the values obtained for $\frac{\epsilon_M}{\nu_L}$ from Equation (3) increase with increasing values of y^+ from a value of zero at the wall ($y^+ = 0$). However, under certain conditions $\frac{\epsilon_M}{\nu_L}$ reaches a maximum within the film, and then decreases. Since this might not be realistic, the program offers two options for the values of $\frac{\epsilon_M}{\nu_L}$ used in succeeding calculations:

a) Option 1 - The program uses the values of $\frac{\epsilon_M}{\nu_L}$ obtained from Equation (3).

b) Option 2 - The program uses the values of $\frac{\epsilon_M}{\nu_L}$ obtained from Equation (3) until $\frac{\epsilon_M}{\nu_L}$ reaches a maximum. Beyond that point this maximum value of $\frac{\epsilon_M}{\nu_L}$ is used.

Once the shear stress distribution and $\frac{\epsilon_M}{\nu_L}$ are obtained, the program solves for the velocity at each radial location by numerical integration of the following equation

$$du^+ = \frac{\frac{\tau}{\tau_o} \, dy^+}{1 + \frac{\epsilon_M}{\nu_L}} \qquad (4)$$

Integration of Equation (4) and all subsequent integrations are performed with the aid of Simpson's rule. A discussion of Simpson's rule appears in Appendix A.

Under certain conditions, integration of Equation (4) can result in negative values of u^+. If this should occur, the program will continue to solve for the desired flow using the absolute value of u^+. In such a case, the program will provide an error printout in addition to its normal printout, since the results of such a case are not valid. See Section V for a discussion on error printouts.

Once the liquid velocities are known at each radial location, the program calculates a liquid flow rate by performing the following integration

$$W_L = \frac{2 \pi \rho_L \nu_L^2}{V^*} \int_0^{y^+ = \delta^+} u^+ (r_o^+ - y^+) \, dy^+ \qquad (5)$$

The final solution is obtained when the value of liquid flow rate calculated in this manner is equal to the input liquid flow rate $(1-x)\,W_T$ within a specified tolerance. Thus, the final solution is obtained when the following condition occurs

$$\frac{/(1-x)\,W_T - W_L/}{(1-x)\,W_T} \leq \text{Tolerance 1} \qquad (6)$$

where Tolerance 1 is a program input item.

However, if the calculated liquid flow rate from this first try is not within the specified tolerance, the program will resort to the use of a false-position subroutine in order to rapidly zero in on a value of liquid fraction which matches the input liquid flow rate $(1-x)\ W_T$.

The false-position subroutine requires two values of liquid fraction which bracket the root. That is, one value of R_L must, when used in Equations (1) through (5), yield a value of liquid flow rate which is less than the input liquid flow rate. Another value of R_L must provide a liquid flow rate greater than the input value. The initial guess of R_L provides one of these values. If the liquid flow rate obtained using the initial guess of liquid fraction R_{Li} is greater than the input liquid flow rate, the program chooses a new value of liquid fraction equal to one-half the initial guess. If the liquid flow rate obtained using $\frac{R_{Li}}{2}$ is less than the input liquid flow rate, the brackets needed for the false-position subroutine are obtained. If the liquid flow rate obtained using $\frac{R_{Li}}{2}$ is greater than the input liquid flow rate, the program calculates liquid flow rate using $\frac{R_{Li}}{4}$, $\frac{R_{Li}}{8}$, $\frac{R_{Li}}{16}$, etc., until a value of liquid fraction for which the calculated liquid flow rate is less than $(1-x)\ W_T$ is obtained.

If the liquid flow rate obtained using the initial value of liquid fraction is less than the input liquid flow rate, the program chooses a new value of liquid fraction equal to twice the initial value if R_{Li} is less than 0.3333, or $\frac{1.0 + R_{Li}}{2}$ if R_{Li} is greater than or equal to 0.3333. If this second value of R_L fails to provide the upper bracket, then another value of R_L is tried by a similar routine until the two bracketing values of liquid fraction are obtained.

The logic of the false-position subroutine used to find the value of liquid friction that matches the input liquid flow rate is described in Appendix B.

After convergence of liquid flow rate is achieved, the program calculates the ratio of eddy diffusivities α at each of the selected radial locations, using the following equation

$$\alpha = \exp\left[\frac{-\text{Alpha Constant 1}}{\left[\frac{\epsilon_M}{\nu_L}\right]^{\text{Alpha Constant 2}}}\right] \qquad (7)$$

Recommended values for the constants in Equation (7) are

Alpha Constant 1 = 2.0
Alpha Constant 2 = 0.5

After evaluating the ratio of eddy diffusivities the program calculates the temperature profile from the following equation

$$t^+ = \int_0^{y^+} \frac{q/q_o}{\frac{1}{Pr_L} + \alpha \frac{\epsilon_M}{\nu_L}} \, dy^+ \quad (8)$$

where

$$\frac{q}{q_o} = \frac{1}{1 - \left(\frac{y^+}{r_o^+}\right)}$$

Once t^+ is evaluated at δ^+, the condensing-heat-transfer coefficient is calculated from the following equation

$$h_{film} = \frac{q_o}{T_v - T_o} = \frac{C_{p_L} \; \rho_L \; V^*}{t^+_{\text{at } y^+ = \delta^+}} \quad (9)$$

This coefficient h_{film} involves only the temperature difference due to the thermal resistance of the liquid film. If liquid-vapor interfacial resistance is present, the program calculates an interfacial resistance coefficient and an overall condensing-heat-transfer coefficient, using the following equations

$$h_{interface} = \left(\frac{\sigma}{2-\sigma}\right) \left(\frac{2}{\pi}\right)^{1/2} \left(\frac{M}{R}\right)^{3/2} \frac{P_{sat}\,\lambda^2}{(t_v)^{5/2}} \; g_c^{1/2} J \qquad (10)$$

$$h = \frac{1}{\dfrac{1}{h_{film}} + \dfrac{1}{h_{interface}}\left(\dfrac{r_o^+ - \delta^+}{r_o^+}\right)} \qquad (11)$$

If a value of zero is input for sigma (σ) the program bypasses the liquid-vapor interfacial resistance calculation. As a result $h = h_{film}$.

III. INPUT INSTRUCTIONS

A. Instructions for First Case

Enter the cards in the following order:

1. Title Card

Enter title in Columns 2 through 72

2. Control Card

The outline below shows the field locations of the various items used to control the program

1 2 3	4 5	6 7
N	ICHANG	IEMNU

All items must be entered as fixed-point right-adjusted numbers.

Symbol	Column	Instruction
N	1 → 3	Enter the number of double intervals used in the calculations (maximum number for N = 499)
ICHANG	4 and 5	Enter zero (0). This instructs the machine that a master case is being loaded.
IEMNU	6 and 7	Enter one (1) in Column 7 to use Option 1. Enter two (2) in Column 7 to use Option 2. See Page 4 for description of Options.

3. Data Cards

Five data cards are entered with the format shown below. (Definitions and units are listed in Table 2, Appendix C). All data input must be entered in floating-point mode within the field widths indicated.

Field Width	1-14	15-28	29-42	43-56	57-70
Card No. 1	T'Sat	P'Sat	Tube Radius	Total Flow	Quality
Card No. 2	Heat Flux	DP/DL Friction	G Field	Cosine Theta	Viscosity (L)
Card No. 3	Viscosity (V)	Specific Heat (L)	Latent Heat	Thermal Cond. (L)	Density (L)
Card No. 4	Density (V)	Mole Weight	Sigma	Alpha Constant 1	Alpha Constant 2
Card No. 5	Tolerance 1	Tolerance 2			

B. Instructions for Each Succeeding Case

The following procedure should be used if it is desired to run more than one case in a loading when only a few input items are to be changed from the preceding case.

Load cards immediately behind the preceding case in the following order:

1. Title Card

Enter 1 in Column 1
Enter title in Columns 2 through 72

2. Control Card

N — Enter one-half the number of double intervals used in the calculations (maximum number for N = 499).

ICHANG — Enter one (1) in Column 5. This instructs the machine that one or more input items from the previous case will be changed.

IEMNU — Enter one (1) in Column 7 to use Option 1. Enter two (2) in Column 7 to use Option 2. See Page 4 for description of options.

3. Input Change Cards

For each input item on data cards to be changed from the preceding case, enter a card with the input as follows:

a. Columns (1 and 2) - Identification number of variable to be changed (see Table 2). Identification number must be entered as a fixed-point right-adjusted number.

b. Columns (3 through 16) - New value of input item in floating-point mode.

4. Blank Card

C. Instructions to End Deck

After the last case input, insert two blank cards.

IV. PRINTOUT FORMAT

A sample of the printout format of the program is shown in Table 3. The information contained in this format is arranged in four blocks which appear in the following order:

Block 1

Block 1 is a tabulation of the input data. Symbols, definitions, and units for the input data appear in Table 2.

Block 2

Block 2 is a tabulation of values of the radially-independent output items. Symbols, definitions, and units of these items appear in Table 4.

Block 3

Block 3 is a tabulation of values of the radially-dependent output items. Symbols, definitions, and units of these items appear in Table 5.

Block 4

Block 4 is a tabulation of the values of liquid flow rate and liquid fraction R_L used in the iteration routine to obtain the final solution.

If a set of conditions are entered so that an unrealistic answer results, or convergence upon an answer is impossible, an error printout will result. See Section V for an explanation of error printouts.

V. ERROR PRINTOUTS

In the event that unusual flow conditions exist or the computer cannot find a liquid flow rate that will satisfy the program equations, an error printout will occur.

Error printouts occur if:

1) The program cannot converge on the proper liquid flow rate W_{liquid} calculated $\neq (1-x)W_T$

2) Negative liquid velocities occur

3) Negative shear stresses occur

4) The calculated value of the Lockhart-Martinelli liquid fraction is greater than or equal to one.

5) The calculated value of the Lockhart-Martinelli liquid fraction is less than or equal to zero.

If Item 1 is the reason for the error printout, the following statement will be printed. "The method of false position failed to iterate". The answers that will be printed are from the last pass through the iteration and are not valid.

If the reason for the error printout is Item 2, the following statement will be printed. "Valid solution not obtained -- negative liquid velocities occur".

If the reason for the error printout is Item 3, the following statement will be printed. "Note: Negative shear stresses occurred".

In the event that Item 4 or 5 is the reason for the error printout, the program will terminate without returning any answers other than listing the input (Block 1). These errors are possible only if an error is made in the program input.

APPENDIX A

Simpson's Rule Integration

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Simpson's Rule Integration

All integration within the program is performed with the aid of Simpson's rule. Simpson's rule provides a rapid method for integrating functions with a high degree of accuracy. It assumes that each section of a function to be integrated can be approximated by a parabola through its ends and midpoint.

The sketch below shows three points of function with a parabolic arc drawn through them. Thus

$$Z = f(y) = Ay^2 + By + C \qquad (A1)$$

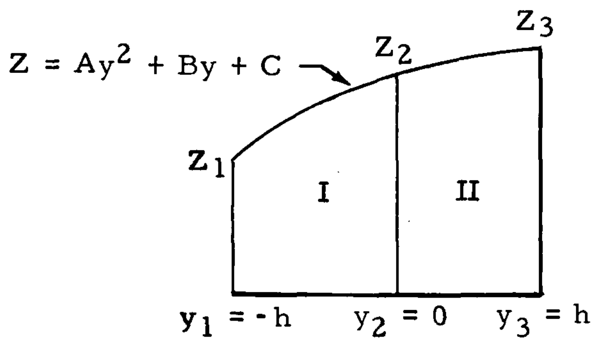


Figure A1

At the midpoint of the double interval shown in the sketch $y = 0$ and $Z = Z_2$

Substituting these values into Equation (A1) and solving for C

$$C = Z_2 \qquad (A2)$$

thus

$$Z = Ay^2 + By + Z_2 \qquad (A3)$$

At the left end point $y = -h$ and $Z = Z_1$

Substituting these values into Equation (A3) gives

$$Z_1 = Ah^2 - Bh + Z_2 \qquad \text{(A4)}$$

At the right end point $y = +h$ and $Z = Z_3$

Substituting these values into Equation (A3) gives

$$Z_3 = Ah^2 + Bh + Z_2 \qquad \text{(A6)}$$

Adding Equations (A4) and (A6) and solving for Ah^2

$$Ah^2 = \frac{Z_1 + Z_3}{2} - Z_2 \qquad \text{(A7)}$$

Subtracting Equation (A4) from Equation (A5) yields

$$Bh = \frac{Z_3 - Z_1}{2} \qquad \text{(A8)}$$

Integrating Equation (A1) between limits of $y_1 = -h$ and $y_2 = 0$ gives

$$\begin{array}{l}\text{Area of} \\ \text{Increment I} \\ \text{(Figure A1)}\end{array} = \int_{y_1 = -h}^{y_2 = 0} f(y)\, dy = h\left(\frac{Ah^2}{3} - \frac{Bh}{2} + C\right) \qquad \text{(A9)}$$

Similarly

$$\begin{array}{l}\text{Area of} \\ \text{Increment II} \\ \text{(Figure A1)}\end{array} = \int_{y_2 = 0}^{y_3 = h} f(y)\, dy = h\left(\frac{Ah^2}{3} + \frac{Bh}{2} + C\right) \qquad \text{(A10)}$$

Substituting Equations (A2), (A7) and (A8) into Equations (A9) and (A10)

$$\int_{-h}^{o} f(y)\,dy = \frac{h}{12}\,(5Z_1 + 8Z_2 - Z_3) \qquad \text{(A11)}$$

$$\int_{o}^{h} f(y)\,dy = \frac{h}{12}\,(-Z_1 + 8Z_2 + 5Z_3) \qquad \text{(A12)}$$

These last two equations provide the integrals of two increments of a function in terms of values of the function at the increment end points.

Equations (A11) and (A12) are the forms of Simpson's rule used throughout the program.

The smaller the width of the increment, the greater will be the accuracy of the approximation. The program can accept up to 499 double intervals (N = 499) and hence 998 increments. However, in few instances will it be necessary to use that many increments.

APPENDIX B

Method of False Position

APPENDIX B

Method of False Position

The principle of false position provides a rapid method for solving iterative problems. The computer program uses a false-position subroutine to obtain a value of liquid fraction R_L corresponding to the input value of liquid flow rate $(1-x)\ W_T$. The false-position subroutine requires

1) the function to be evaluated be a monotonic function, and
2) values of liquid fraction with corresponding liquid flow rates that bracket the desired root.

The method of false position can be explained with the aid of Figures B1 through B4. Assume that Figure B1 shows the true relationship between liquid flow rate and liquid fraction.

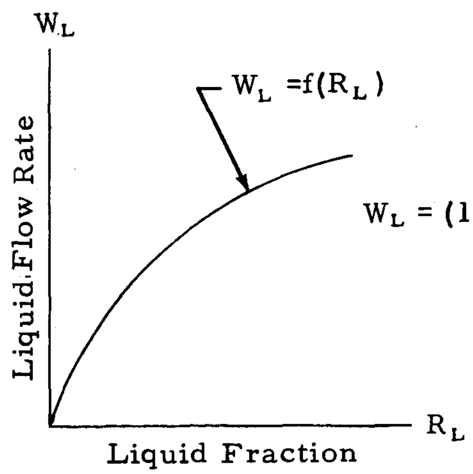


Figure B1

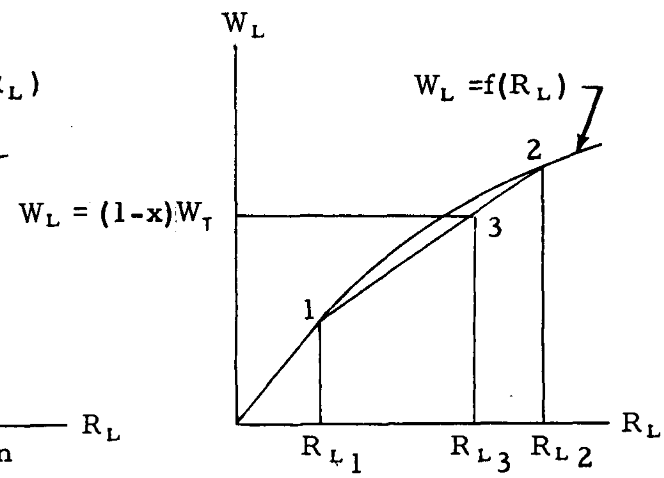


Figure B2

In Figure B2, R_{L1} and R_{L2} correspond to the values of liquid fraction known to bracket the correct answer (see page 6 for a discussion of the method used to bracket the correct answer). The program determines where a straight line through Points 1 and 2 intersects the horizontal line $W_L = (1-x)\ W_T$. This point corresponds to a new guessed value for R_L (namely R_{L3}).

Using Equations (1) through (5) of Section IV, the program calculates the value of liquid flow rate corresponding to R_{L_3}, which is W_{L_4} (Point 4) on Figure B3. Straight lines are then determined between Points 1 and 4 and Points 2 and 4, intersecting $W_L = (1-x)\,W_T$ at Points 5 and 6, respectively. R_{L_5} and R_{L_6} bracket the solution.

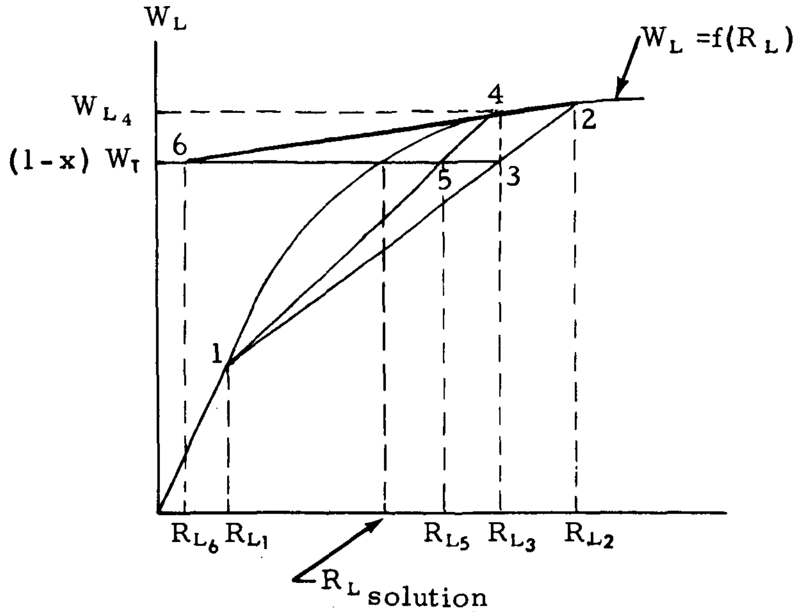


Figure B3

The program then selects the two values of R_L which provide bracketing liquid flows closest to the true liquid flow rate, and uses them as the new brackets (in this case, R_{L_1} and R_{L_5}) to continue the process.

After each process, the program checks to see whether or not the difference between the R_L brackets is within a specified tolerance.

It checks if $\dfrac{/R_{L_5} - R_{L_1}/}{/R_{L_5} + R_{L_1}/}$ is less than, greater than, or equal to

Tolerance 2 where Tolerance 2 is a program input item.

a) If $\dfrac{/R_{L_5} - R_{L_1}/}{/R_{L_5} + R_{L_1}/} \leq$ Tolerance 2, the program picks a new value of liquid fraction $R_{L7} = \dfrac{R_{L5} + R_{L1}}{2}$ and evaluates a corresponding liquid flow rate W_{L7} on Figure B4.

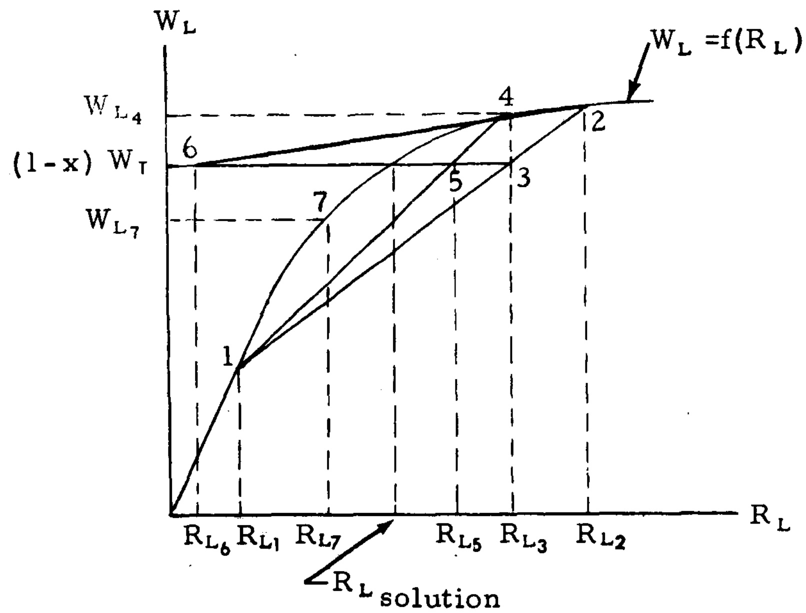


Figure B4

The program then checks whether or not W_{L7} matches $(1-x)\,W_T$ within a specified tolerance.

It checks if $\dfrac{/W_{L7} - (1-x)\,W_T/}{(1-x)W_T}$ is less than, greater than, or equal to Tolerance 1.

where Tolerance 1 is a program input item.

If $\dfrac{/W_{L7} - (1-x)\,W_T/}{(1-x)W_T} \leq$ Tolerance 1,

convergence on liquid flow rate is attained, and the velocity profile and film thickness corresponding to W_{L7} and R_{L7} are the final answers.

If $\dfrac{/W_{L7} - (1-x)W_T/}{(1-x)W_T} >$ Tolerance 1,

the program decreases Tolerance 2 by a factor of 10 and repeats the iteration process using R_{L1} and R_{L5} as the left and right brackets respectively.

b) If $\frac{/R_{L_5} - R_{L_1}/}{R_{L_5} + R_{L_1}}$ > Tolerance 2,

the program repeats the iteration process using R_{L_1} and R_{L_5} as the left and right brackets. If there is no convergence upon liquid fraction and liquid flow rate after 30 iterations, the program prints out the last calculated values of liquid fraction and liquid flow rate along with an error printout stating that the method of false position failed to iterate. If this happens, it is probably due to an input error.

APPENDIX C

Tables

TABLE 1

Nomenclature

Symbol	Definition	Units
Alpha Constant 1	constant defined in Equation (7)	--
Alpha Constant 2	constant defined in Equation (7)	--
Cp	fluid specific heat	Btu /lb_m °F
$dp/d\ell$	static pressure gradient	lb_f/ft^3
g	local gravitational acceleration	ft/hr^2
g_c	Newton's conversion factor	lb_m ft/lb_f hr^2
h	local condensing-heat-transfer coefficient	Btu /hr ft^2 °F
h_{film}	heat-transfer coefficient due to liquid film thermal resistance	Btu/hr ft^2 °F
$h_{interface}$	heat-transfer coefficient due to liquid vapor interfacial resistance	Btu/hr ft^2 °F
J	thermal conversion factor (778 ft lb_f/Btu)	--
M	molecular weight	lb_m/lb-mole
N	number of double intervals used in calculations	--
P_{sat}	vapor saturation pressure	lb_f/ft^2
Pr	Prandtl number	--
q	heat flux	Btu/hr ft^2
R	universal gas constant	ft lb_f/lb-mcle °R
R_L	liquid fraction	--
r_o	tube inner radius	ft
r_o^+	dimensionless tube inner radius	--
T_o	wall temperature	°F
T_v	fluid saturation temperature	°F
t_v	fluid saturation temperature	°R
t^+	dimensionless fluid temperature	--
Tolerance 1	tolerance on liquid flow rate (see Appendix B)	--
Tolerance 2	tolerance on liquid fraction (see Appendix B)	--
u^+	dimensionless liquid velocity	--
V*	friction velocity $\sqrt{\tau_o g_c/\rho_L}$	ft/hr
W_L	liquid flow rate	lb_m/hr
W_T	total flow rate (liquid + vapor)	lb_m/hr

TABLE 1 (Cont'd.)

X	Lockhart-Martinelli two-phase flow parameter	--
x	fluid quality $= \frac{W_g}{W_T}$	--
y	distance measured from wall	ft
y^+	dimensionless distance measured from wall	--
α	ratio of eddy diffusivity of heat to eddy diffusivity of momentum	--
δ^+	dimensionless thickness of liquid film	--
ϵ_M	eddy diffusivity of momentum	ft^2/hr
θ	angle of tube orientation measured from vertically upward	
λ	latent heat of vaporization	Btu/lb_m
ν	kinematic viscosity	ft^2/hr
ρ	density	lb_m/ft^3
σ	condensation coefficient, see Equation (10)	--
τ	shear stress	lb_f/ft^2

Subscripts

Symbol	Definition
g	refers to vapor
i	refers to initial guess
L	refers to liquid
o	refers to conditions at the wall

TABLE 2

Input Data

Variable Identification Number	Symbol	Definition	Units
1	T'Sat	fluid saturation temperature	°F
2	P'Sat	fluid saturation pressure	lb_f/ft^2
3	Tube Radius	tube inner radius	ft
4	Total Flow	total flow rate	lb_m/hr
5	Quality	fluid quality, x	--
6	Heat Flux	heat flux	Btu/hr ft^2
7	DP/DL Friction	absolute value of frictional pressure gradient	lb_f/ft^3
8	G Field	gravity field (g/g_c)	--
9	Cosine Theta	cosine θ (θ measured from vertically upward axis)	--
10	Viscosity (L)	liquid dynamic viscosity, μ_L	lb_m/hr ft
11	Viscosity (V)	vapor dynamic viscosity, μ_g	lb_m/hr ft
12	Specific Heat (L)	liquid specific heat	Btu/lb_m °F
13	Latent Heat	latent heat of vaporization	Btu/lb_m
14	Thermal Cond (L)	liquid thermal conductivity	Btu/hr ft °F
15	Density (L)	liquid density	lb_m/ft^3
16	Density (V)	vapor density	lb_m/ft^3
17	Mole Weight	fluid molecular weight	lb_m/lb-mole
18	Sigma	condensation coefficient appearing in Equation(10)	--
19	Alpha Constant 1	constant appearing in Equation (7)	--
20	Alpha Constant 2	constant appearing in Equation (7)	--
21	Tolerance 1	tolerance on liquid flow (see Appendix B)	--
22	Tolerance 2	tolerance on liquid fraction (see Appendix B)	--

TABLE 3
Sample Printout

BLOCK 1

NASA RUN 164 X = .912 (DP/DL)FR = L-M

NUMBER OF DOUBLE INCREMENTS	ICHANGE	EMNU OPTION
20	0	2

T'SAT	P'SAT	TUBE RADIUS	TOTAL FLOW	QUALITY
0.22900E 03	0.29600E 04	0.12225E-01	0.46220E 02	0.91200E 00
HEAT FLUX	DP/DL FRICTION	G FIELD	COSINE THETA	
0.15700E 06	0.18460E 03	0.10000E 01	-0.10000E 01	
VISCOSITY (L)	VISCOSITY (V)	SPECIFIC HEAT(L)	LATENT HEAT	THERMAL COND (L)
0.62000E 00	0.32700E-01	0.10000E 01	0.95900E 03	0.39500E-00
DENSITY (L)	DENSITY (V)	MOLE WEIGHT	SIGMA	
0.59400E 02	0.51200E-01	0.18000E 02	0.	
ALPHA CONSTANT 1	ALPHA CONSTANT 2	TOLERANCE 1	TOLERANCE 2	
0.20000E 01	0.50000E 00	1.00000E-02	1.00000E-02	

BLOCK 2

FILM THICKNESS	DELTA (PLUS)
0.52451E-04	0.14143E 02

H(OVERALL)	H(FILM)	H(LIQ'VAP INTERFACE)	T'WALL	T'WALL(H=HFILM)	T'INTERFACE
0.83166E 04	0.83166E 04	0.	0.	0.21012E 03	0.22900E 03
DP/DL(TOTAL)	DP/DL(FRICTION)	DP/DL(HEAD)	DP/DL(MOM)	DP/DL(MOM'LIQ)	DP/DL(MOM'VAP)
-0.37156E 02	0.18460E 03	-0.55937E 00	-0.22120E 03	0.17271E 01	-0.22292E 03
REYNOLDS NO (LIQ)	REYNOLDS NO (VAP)	V (STAR)	RL (CALC)	RL (L'M)	CALC LIQUID FLOW
0.34163E 03	0.67129E 05	0.28144E 04	0.85625E-02	0.82006E-02	0.40674E 01

TABLE 3 (Cont)

BLOCK 3

Y/RO	Y	Y(PLUS)	T(PLUS)	U(PLUS)	ALPHA	EPSILON M/NU	TAU/TAUO
0.	0.	0.	0.	0.	0.	0.	0.10000E 01
0.10726E-03	0.13113E-05	0.35357E-00	0.55500E 00	0.35358E-00	0.	0.36508E-05	0.10001E 01
0.21452E-03	0.26225E-05	0.70714E 00	0.11101E 01	0.70719E 00	0.	0.57600E-04	0.10002E 01
0.32178E-03	0.39338E-05	0.10607E 01	0.16652E 01	0.10608E 01	0.	0.28766E-03	0.10002E 01
0.42905E-03	0.52451E-05	0.14143E 01	0.22204E 01	0.14143E 01	0.97821E-29	0.89649E-03	0.10003E 01
0.53631E-03	0.65564E-05	0.17678E 01	0.27756E 01	0.17674E 01	0.19840E-18	0.21569E-02	0.10004E 01
0.64357E-03	0.78676E-05	0.21214E 01	0.33309E 01	0.21200E 01	0.81390E-13	0.44034E-02	0.10005E 01
0.75083E-03	0.91789E-05	0.24750E 01	0.38863E 01	0.24717E 01	0.20027E-09	0.80210E-02	0.10006E 01
0.85809E-03	0.10490E-04	0.28286E 01	0.44417E 01	0.28218E 01	0.32000E-07	0.13431E-01	0.10007E 01
0.96535E-03	0.11801E-04	0.31821E 01	0.49971E 01	0.31696E 01	0.10383E-05	0.21071E-01	0.10007E 01
0.10726E-02	0.13113E-04	0.35357E 01	0.55527E 01	0.35145E 01	0.12489E-04	0.31378E-01	0.10008E 01
0.11799E-02	0.14424E-04	0.38893E 01	0.61083E 01	0.38555E 01	0.78404E-04	0.44757E-01	0.10009E 01
0.12871E-02	0.15735E-04	0.42428E 01	0.66639E 01	0.41917E 01	0.31586E-03	0.61570E-01	0.10010E 01
0.13944E-02	0.17047E-04	0.45964E 01	0.72196E 01	0.45220E 01	0.93061E-03	0.82109E-01	0.10011E 01
0.15017E-02	0.18358E-04	0.49500E 01	0.77752E 01	0.48455E 01	0.21856E-02	0.10659E-00	0.10011E 01
0.16089E-02	0.19669E-04	0.53035E 01	0.83308E 01	0.51614E 01	0.43386E-02	0.13515E-00	0.10012E 01
0.17162E-02	0.20980E-04	0.56571E 01	0.88859E 01	0.54690E 01	0.75854E-02	0.16786E-00	0.10013E 01
0.18234E-02	0.22292E-04	0.60107E 01	0.94402E 01	0.57676E 01	0.12029E-01	0.20470E-00	0.10014E 01
0.19307E-02	0.23603E-04	0.63643E 01	0.99933E 01	0.60567E 01	0.17678E-01	0.24563E-00	0.10015E 01
0.20380E-02	0.24914E-04	0.67178E 01	0.10545E 02	0.63360E 01	0.24465E-01	0.29053E-00	0.10016E 01
0.21452E-02	0.26225E-04	0.70714E 01	0.11093E 02	0.66054E 01	0.32273E-01	0.33930E-00	0.10016E 01
0.22525E-02	0.27537E-04	0.74250E 01	0.11638E 02	0.68649E 01	0.40956E-01	0.39178E-00	0.10017E 01
0.23598E-02	0.28848E-04	0.77785E 01	0.12178E 02	0.71144E 01	0.50359E-01	0.44785E-00	0.10018E 01
0.24670E-02	0.30159E-04	0.81321E 01	0.12712E 02	0.73542E 01	0.60331E-01	0.50733E 00	0.10019E 01
0.25743E-02	0.31471E-04	0.84857E 01	0.13239E 02	0.75845E 01	0.70734E-01	0.57010E 00	0.10020E 01
0.26815E-02	0.32782E-04	0.88392E 01	0.13758E 02	0.78056E 01	0.81445E-01	0.63601E 00	0.10020E 01
0.27888E-02	0.34093E-04	0.91928E 01	0.14268E 02	0.80178E 01	0.92358E-01	0.70493E 00	0.10021E 01
0.28961E-02	0.35404E-04	0.95464E 01	0.14768E 02	0.82213E 01	0.10338E-00	0.77674E 00	0.10022E 01
0.30033E-02	0.36716E-04	0.99000E 01	0.15256E 02	0.84167E 01	0.11445E-00	0.85132E 00	0.10023E 01
0.31106E-02	0.38027E-04	0.10254E 02	0.15733E 02	0.86043E 01	0.12549E-00	0.92856E 00	0.10024E 01
0.32178E-02	0.39338E-04	0.10607E 02	0.16197E 02	0.87844E 01	0.13646E-00	0.10084E 01	0.10025E 01
0.33251E-02	0.40649E-04	0.10961E 02	0.16649E 02	0.89574E 01	0.14733E-00	0.10906E 01	0.10025E 01
0.34324E-02	0.41961E-04	0.11314E 02	0.17087E 02	0.91236E 01	0.15805E-00	0.11753E 01	0.10026E 01
0.35396E-02	0.43272E-04	0.11668E 02	0.17511E 02	0.92834E 01	0.16861E-00	0.12622E 01	0.10027E 01
0.36469E-02	0.44583E-04	0.12021E 02	0.17921E 02	0.94372E 01	0.17899E-00	0.13514E 01	0.10028E 01
0.37542E-02	0.45895E-04	0.12375E 02	0.18318E 02	0.95851E 01	0.18917E-00	0.14427E 01	0.10029E 01
0.38614E-02	0.47206E-04	0.12729E 02	0.18701E 02	0.97276E 01	0.19916E-00	0.15361E 01	0.10029E 01
0.39687E-02	0.48517E-04	0.13082E 02	0.19071E 02	0.98648E 01	0.20893E-00	0.16316E 01	0.10030E 01
0.40759E-02	0.49828E-04	0.13436E 02	0.19428E 02	0.99972E 01	0.21849E-00	0.17289E 01	0.10031E 01
0.41832E-02	0.51140E-04	0.13789E 02	0.19771E 02	0.10125E 02	0.22783E-00	0.18282E 01	0.10032E 01
0.42905E-02	0.52451E-04	0.14143E 02	0.20102E 02	0.10248E 02	0.23696E-00	0.19293E 01	0.10033E 01

BLOCK 4

CALCULATED RL	CALCULATED LIQUID FLOW
0.82006E-02	0.37792E 01
0.16401E-01	0.11349E 02
0.82006E-02	0.37792E 01
0.16401E-01	0.11349E 02
0.85127E-02	0.40274E 01
0.85630E-02	0.40678E 01
0.85558E-02	0.40620E 01
0.85625E-02	0.40674E 01

TABLE 4

Radially-Independent Printout Items

Symbol	Definition	Units
Calc. Liquid Flow	liquid flow rate obtained using final value of liquid fraction in Equations (1) to (5)	lb_m/hr
DELTA (Plus)	dimensionless film thickness	--
DP/DL (Friction)	*frictional pressure gradient	lb_f/ft^3
DP/DL (Head)	*pressure gradient due to static head	lb_f/ft^3
DP/DL (Mom)	*static pressure gradient due to liquid and vapor momentum	lb_f/ft^3
DP/DL (Mom'Liq)	*static pressure gradient due to liquid momentum	lb_f/ft^3
DP/DL (Mom'Vap)	*static pressure gradient due to vapor momentum	lb_f/ft^3
DP/DL (Total	*static pressure gradient due to friction, static head,and momentum	lb_f/ft^3
Film Thickness	film thickness	ft
H (Film)	heat transfer coefficient based on liquid layer resistance	Btu/hr ft^2 °F
H (Overall)	overall heat transfer coefficient, see Equation (11)	Btu/hr ft^2 °F
H (Liq'Vap Interface)	heat transfer coefficient due to interfacial resistance, see Equation (10)	Btu/hr ft^2 °F
Reynolds No. (Liq)	full bore liquid Reynolds number $\frac{2W_L}{\pi r_o \mu_L}$	--
Reynolds No. (Vap)	full bore vapor Reynolds number $\frac{2 x W_T}{\pi r_o \mu_g}$	--
RL (Calc)	final value of liquid fraction	--
RL (L'M)	liquid fraction obtained from Lockhart-Martinelli correlation	--

* $dp/d\ell$ used here is the negative of the true pressure gradient and therefore a negative static pressure gradient indicates a pressure rise in the direction of flow

TABLE 4 (Cont'd.)

T'INTERFACE	*liquid temperature at liquid-vapor interface	°F
T'WALL	wall temperature in presence of interfacial resistance	°F
T'WALL(H = HFilm)	wall temperature when interfacial resistance is neglected	°F
V (STAR)	friction velocity = $\sqrt{\tau_o g_c / \rho_L}$	ft/hr

* When no liquid-vapor interfacial resistance is considered, the temperature at the liquid vapor interface is the saturation temperature

TABLE 5

Radially-Dependent Printout Items

Symbol	Definition	Units
Alpha	ratio of eddy diffusivity of heat to eddy diffusivity of momentum, $(\epsilon_H / \epsilon_M)$	--
Epsilon M/NU	ratio of eddy diffusivity of momentum to liquid kinematic viscosity, (ϵ_M / ν_L)	--
Tau/Tauo	ratio of local shear stress to shear stress at wall, (τ / τ_o)	--
T (Plus)	dimensionless temperature, t^+	--
U (Plus)	dimensionless velocity, u^+	--
Y	distance from wall, y	ft
Y (Plus)	dimensionless distance measured from wall, y^+	--
Y/RO	ratio of distance measured from wall to tube inner radius, y/r_o	--

APPENDIX D

List of Computer Statements

```
CDKA443
CMAIN PROGRAM
      COMMON  BLK,ANS,RES,CAL
      EQUIVALENCE   (BLK( 1),TSAT   ),(BLK( 2),PSAT   ),(BLK( 3),RO     ),
     1              (BLK( 4),WTOT   ),(BLK( 5),X      ),(BLK( 6),QO     ),
     2              (BLK( 7),DPDLFR),(BLK( 8),GRAT   ),(BLK( 9),COSTHA),
     3              (BLK(10),VISCL  ),(BLK(11),VISCG  ),(BLK(12),CPL    ),
     4              (BLK(13),ZAMBDA),(BLK(14),ZKL    ),(BLK(15),RHOL   ),
     5              (BLK(16),RHOG   ),(BLK(17),ZMOL   ),(BLK(18),SIGMA  ),
     6              (BLK(19),CONAL1),(BLK(20),CONAL2),(BLK(21),TOL1   ),
     7              (BLK(22),TOL2   )
      EQUIVALENCE   (ANS( 1),DELTA  ),(ANS( 2),ETA    ),(ANS( 3),H      ),
     1              (ANS( 4),HFILM  ),(ANS( 5),HINT   ),(ANS( 6),TWSRJ  ),
     2              (ANS( 7),TWNSRJ),(ANS( 8),TINT   ),(ANS( 9),SMDPDL),
     3              (ANS(10),OFR    ),(ANS(11),DPDLSH),(ANS(12),DPDLM  ),
     4              (ANS(13),DPDLML),(ANS(14),DPDLMG),(ANS(15),REL    ),
     5              (ANS(16),REG    ),(ANS(17),VSTAR  ),(ANS(18),RL     ),
     6              (ANS(19),RLLM   ),(ANS(20),WFLOL  )
      EQUIVALENCE(RES(    1),YPLRO),(RES(1001),Y      ),(RES(2001),YPL   ),
     1           (RES(3001),TPL   ),(RES(4001),UPL    ),(RES(5001),ALPHA),
     2           (RES(6001),EMNUL),(RES(7001),TAURAT),(RES(8001),ORL   ),
     3           (RES(8201),OWTL  ),(RES(8401),ABUPL),(RES(9401),ABTAUR)
      EQUIVALENCE   (CAL(    1),FYPL),(CAL(1001),GYPL),(CAL(2001),ZYP   ),
     1              (CAL(3001),CX    ),(CAL(3002),PRL  ),(CAL(3003),DXDL  ),
     2              (CAL(3004),PI    ),(CAL(3005),N    ),(CAL(3006),L     ),
     3              (CAL(3007),M     ),(CAL(3008),NOIT),(CAL(3009),IEMNU)
      DIMENSION  YPLRO (1000),Y      (1000),YPL    (1000),TPL     (1000),
     1           UPL   (1000),ALPHA (1000),EMNUL  (1000),TAURAT  (1000),
     2           ORL   ( 200),OWTL  ( 200),FYPL   (1000),GYPL    (1000),
     3           ZYP   (1000),BLK   (   22),ANS    (   20),RES  (10400),
     4           CAL   (3009),HOLL  (   14),ABUPL (1000),ABTAUR (1000)
F     FWFLOL
      IPRINT = 1
      NN = 2
      MM = 3
  500 WRITE OUTPUT TAPE NN,555
```

```
501 READ INPUT TAPE MM,502,HOLL
    WRITE OUTPUT TAPE NN,602,HOLL
    READ INPUT TAPE MM,503,N,ICHANG,IEMNU
     IF (N) 2000,2000,507
504 READ INPUT TAPE MM,508,I,TEMPER
     IF (I) 510,510,509
505 READ INPUT TAPE MM,506,(BLK(I),I=1,22)
     GO TO 510
507  IF (ICHANG) 504,505,504
509  BLK(I) = TEMPER
     GO TO 504
510 WRITE OUTPUT TAPE NN,511,N,ICHANG,IEMNU
    WRITE OUTPUT TAPE NN,512,(BLK(I),I=1,14)
    WRITE OUTPUT TAPE NN,513,(BLK(I),I=15,22)
    DO 514  I=1,20
514  ANS(I) = 0.0
     NOIT = 0
     M = 2*N
     GC = 32.17405
     GCH = GC*1.296E7
     L =  0
     TC = 3600.
     PI = 3.14159265
     OFR = DPDLFR
     PRL = VISCL*CPL/ZKL
     WLIQ = WTOT*(1.0-X)
     WGAS = WTOT*X
     REL = 2.0*WLIQ/PI/RO/VISCL
     REG = 2.0*WGAS/PI/RO/VISCG
     TAUO = RO/2.0*DPDLFR
     VSTAR = SQRTF(TAUO/RHOL*GCH)
     ROPLUS = RO*VSTAR*RHOL/VISCL
     DXDL = -2.0*PI/WTOT*Q0/ZAMBDA*RO
     CALL SRLLM
    SUMUPL = 0.0
    SABUPL = 0.0
```

```
      SMTAUR = 0.0
      SABTAU = 0.0
      IF (RLLM -1.0) 1,1000,1000
    1 IF (RLLM) 1001,1001,2
    2 RL = RLLM
      WFLOL = FWFLOL(RL)
   22 IF (WFLOL - WLIQ) 3,100,8
    3 RLL = RL
      IF (RL - .3333) 4,5,5
    4 RL = 2.0 * RL
      GO TO 6
    5 RL = (1.0 + RL)/2.0
    6 WFLOL = FWFLOL(RL)
      IF (WFLOL - WLIQ) 3,100,7
    7 RLR = RL
      GO TO 10
    8 RLR = RL
      RL = RL/2.0
      WFLOL = FWFLOL(RL)
      IF (WFLOL - WLIQ) 9,100,8
    9 RLL = RL
   10 RL = FALSY(FWFLOL,RLL,RLR,TOL2,WLIQ,NOIT,WLIQC)
      IF (ABSF(1.0-WLIQC/WLIQ) - TOL1) 100,100,11
   11 TOL2 = TOL2/10.
      IF (NOIT - 29) 10,100,100
  100 DELTA = ETA/RHOL*VISCL/VSTAR
      IF (Q0) 101,108,101
  108 MP = M + 1
      DO 109 I = 1,MP
      ALPHA(I) = 0.0
      TPL(I) = 0.0
  109 CONTINUE
      GO TO 106
  101 MP = M + 1
      DO 102 I=1,MP
      ALPHA(I) = EXPF(-CONAL1/(EMNUL(I)**CONAL2))
      Y(I) = YPL(I)*VISCL/RHOL/VSTAR
```

```
      ZYP(I) =  RO/(RO-Y(I))/(1./PRL + ALPHA(I)*EMNUL(I))
  102 CONTINUE
      TPL(1) = 0.0
      ALPHA(1) = 0.0
      DELYPL = ETA/FLOATF(M)
  103 DO 104 I=1,N
      J = 2 * I
      JP= J + 1
      JM= J - 1
      DLTPLL = DELYPL/12.*(5.0*ZYP(JM) + 8.0*ZYP(J) - ZYP(JP))
      DLTPLR = DELYPL/12.*(-ZYP(JM) + 8.0*ZYP(J) + 5.0*ZYP(JP))
      TPL(J) = TPL(JM) + DLTPLL
      TPL(JP) = TPL(J) + DLTPLR
  104 CONTINUE
      TPLS= TPL(JP)
      HFILM = CPL*RHOL*VSTAR/TPLS
      TWNSRJ = TSAT - QO/HFILM
      IF (SIGMA) 105,23,105
   23 H = HFILM
      TINT = TSAT
      GO TO 106
  105 TSATR =(TSAT+460.)**2.5
      HINT = SIGMA/(2.0-SIGMA)*(2.0*GCH/PI)**.5*(ZMOL/1545.)**1.5*PSAT*
     1ZAMBDA*ZAMBDA*778./TSATR
      H = 1.0/(1.0/HFILM + RO/(RO-DELTA)/HINT)
      TWSRJ = TSAT - QO/H
      TINT = TSAT - QO/(HINT*(RO-DELTA)/RO)
  106 VLBARC = WLIQC/RHOL/PI/RO/RO/RL
      MP = M+1
      VAR = VISCL/RHOL/VSTAR
      DO 107  I = 1,MP
      Y(I) = YPL(I)*VAR
  107 CONTINUE
  999 WFLOL = WLIQ
      SMDPDL = - SMDPDL
      DPDLSH = -DPDLSH
```

```
      WRITE OUTPUT TAPE NN,998,(ANS(I),I=1,8)
      WRITE OUTPUT TAPE NN,997,(ANS(I),I=9,20)
      WRITE OUTPUT TAPE NN,996
       MP = M + 1
       DO 917 I=1,MP
  915 WRITE OUTPUT TAPE NN,916, YPLRO(I),Y(I),YPL(I),TPL(I),UPL(I),ALPHA
     1(I),EMNUL(I),TAURAT(I)
      ABUPL(I) = ABSF(UPL(I))
      ABTAUR(I) = ABSF(TAURAT(I))
      SUMUPL = SUMUPL + UPL(I)
      SMTAUR = SMTAUR + TAURAT(I)
      SABUPL = SABUPL + ABUPL(I)
      SABTAU = SABTAU + ABTAUR(I)
  917  CONTINUE
      IF (SABUPL - SUMUPL) 925,925,1002
 1002 WRITE OUTPUT TAPE NN,1102
      GO TO  924
  925 IF (SABTAU - SMTAUR) 924,924,1003
 1003 WRITE OUTPUT TAPE NN,1103
  924 WRITE OUTPUT TAPE NN,918
       DO 920 I=1,L
      WRITE OUTPUT TAPE NN,919,ORL(I),OWTL(I)
  920  CONTINUE
       DO 921 I = 1,L
       ORL(I)=0.0
       OWTL(I) = 0.0
  921  CONTINUE
       GO TO 501
 1000 WRITE OUTPUT TAPE NN,1100
       GO TO 501
 1001 WRITE OUTPUT TAPE NN,1101
       GO TO 501
  502  FORMAT (14A5)
  503  FORMAT (I3,2I2)
  506  FORMAT (5E14.5)
  508  FORMAT (I2,E14.5)
```

```
511 FORMAT (120H0 NUMBER OF DOUBLE INCREMENTS        ICHANGE     EMNU OP
   1ITION
   2/15X,I3,20X,I3,11X,I3)
512 FORMAT (120H0            T'SAT                 P'SAT           TUBE
   1RADIUS          TOTAL FLOW          QUALITY
   2/5(5X,E15.5) /
   3          120H0        HEAT FLUX         DP/DL FRICTION            G F
   4IELD            COSINE THETA
   5/4(5X,E15.5) /
   6          120H0       VISCOSITY (L)       VISCOSITY (V)        SPECIFI
   7C HEAT(L)        LATENT HEAT        THERMAL COND (L)
   8/5(5X,E15.5)/)
513 FORMAT (120H0         DENSITY (L)         DENSITY (V)         MOLE W
   1EIGHT              SIGMA
   2/4(5X,E15.5)/
   3          120H0      ALPHA CONSTANT 1     ALPHA CONSTANT 2        TOLER
   4ANCE 1           TOLERANCE 2
   5/4(5X,E15.5)/)
555 FORMAT(90H1PRATT AND WHITNEY AIRCRAFT CONDENSING HEAT TRANSFER COE
   1FFICIENT PROGRAM                                             ///   )
602  FORMAT (/////14A5)
916  FORMAT(8E15.5)
918 FORMAT (110H0                    CALCULATED RL           CALCULATED L
   2IQUID FLOW                                                         )
919  FORMAT(16X,E15.5,13X,E15.5)
996 FORMAT (120H0        Y/R0                Y               Y(PLUS)         T(P
   1LUS)         U(PLUS)          ALPHA          EPSILON M/NU       TAU/TAU0
   2/)
997 FORMAT (120H0         DP/DL(TOTAL)          DP/DL(FRICTION)         DP/DL
   1(HEAD)          DP/DL(MOM)          DP/DL(MOM'LIQ)        DP/DL(MOM'VAP)
   2//6(5X,E15.5)////
   3          120H0       REYNOLDS NO (LIQ)    REYNOLDS NO (VAP)           V (
   4STAR)              RL (CALC)              RL (L'M)         CALC LIQUID FLOW
   5//6(5X,E15.5)/////)
998 FORMAT(////41H0        FILM THICKNESS           DELTA (PLUS)//2(5X,E15.
   15)////
   2120H0          H(OVERALL)               H(FILM)         H(LIQ'VAP INTERFA
```

```
     3CE)      T'WALL             T'WALL(H=HFILM)        T'INTERFACE       //
     46(5X,E15.5)////)
 1100 FORMAT  (45H0 RL (L-M) IS GREATER THAN OR EQUAL TO ONE           )
 1101 FORMAT (45H0  RL (L-M) IS LESS THAN OR EQUAL TO ZERO             )
 1102 FORMAT(///70H VALID SOLUTION NOT OBTAINED - - - NEGATIVE LIQUID VE
     1LOCITIES OCCUR   //)
 1103 FORMAT(///45H NOTE - - - NEGATIVE SHEAR STRESSES OCCURRED        //)
 2000  CALL EXIT
      END
CFWFLOL
       FUNCTION   FWFLOL(VL)
      COMMON  BLK,ANS,RES,CAL
      EQUIVALENCE   (BLK( 1),TSAT   ),(BLK( 2),PSAT   ),(BLK( 3),RO     ),
     1              (BLK( 4),WTOT   ),(BLK( 5),X      ),(BLK( 6),QO     ),
     2              (BLK( 7),DPDLFR),(BLK( 8),GRAT   ),(BLK( 9),COSTHA),
     3              (BLK(10),VISCL ),(BLK(11),VISCG ),(BLK(12),CPL    ),
     4              (BLK(13),ZAMBDA),(BLK(14),ZKL    ),(BLK(15),RHOL   ),
     5              (BLK(16),RHOG   ),(BLK(17),ZMOL   ),(BLK(18),SIGMA ),
     6              (BLK(19),CONAL1),(BLK(20),CONAL2),(BLK(21),TOL1   ),
     7              (BLK(22),TOL2   )
      EQUIVALENCE   (ANS( 1),DELTA ),(ANS( 2),ETA    ),(ANS( 3),H      ),
     1              (ANS( 4),HFILM ),(ANS( 5),HINT   ),(ANS( 6),TWSRJ ),
     2              (ANS( 7),TWNSRJ),(ANS( 8),TINT   ),(ANS( 9),SMDPDL),
     3              (ANS(10),OFR    ),(ANS(11),DPDLSH),(ANS(12),DPDLM ),
     4              (ANS(13),DPDLML),(ANS(14),DPDLMG),(ANS(15),REL    ),
     5              (ANS(16),REG    ),(ANS(17),VSTAR ),(ANS(18),RL     ),
     6              (ANS(19),RLLM   ),(ANS(20),WFLOL )
      EQUIVALENCE(RES(   1),YPLRO),(RES(1001),Y      ),(RES(2001),YPL   ),
     1          (RES(3001),TPL   ),(RES(4001),UPL    ),(RES(5001),ALPHA),
     2          (RES(6001),EMNUL),(RES(7001),TAURAT),(RES(8001),ORL    ),
     3          (RES(8201),OWTL  ),(RES(8401),ABUPL),(RES(9401),ABTAUR)
      EQUIVALENCE   (CAL(   1),FYPL),(CAL(1001),GYPL),(CAL(2001),ZYP   ),
     1              (CAL(3001),CX   ),(CAL(3002),PRL ),(CAL(3003),DXDL ),
     2              (CAL(3004),PI   ),(CAL(3005),N   ),(CAL(3006),L     ),
     3              (CAL(3007),M    ),(CAL(3008),NOIT),(CAL(3009),IEMNU)
      DIMENSION  YPLRO (1000),Y      (1000),YPL   (1000),TPL    (1000),
```

```
     1          UPL     (1000),ALPHA (1000),EMNUL (1000),TAURAT (1000),
     2          ORL     ( 200),OWTL  ( 200),FYPL  (1000),GYPL   (1000),
     3          ZYP     (1000),BLK   (   22),ANS  (   20),RES  (10400),
     4          CAL     (3009),HOLL  (   14),ABUPL (1000),ABTAUR (1000)
      RL = VL
      IEMNU = IEMNU
      VDK = 0.4
      APLUS = 26.
      IF (RL) 100,100,101
100   WL = 0.0
      GO TO 3
101   IF (RL - 1.0) 102,103,103
103   RL = .9999
102   B = 2.0*PI*VISCL *VISCL/VSTAR/RHOL
      ROPLUS = RO*VSTAR*RHOL/VISCL
      TAUO = RO/2.0*DPDLFR
      DPDLSH = -COSTHA*GRAT*(RL*RHOL + (1.0-RL)*RHOG)
      CALL SDPDLM
      SMDPDL = -DPDLFR - DPDLM + DPDLSH
      ETA = ROPLUS*(1.0 - SQRTF(1.0-RL))
      DELYPL = ETA/FLOATF(M)
      DUMP1 = RO/2.0/TAUC*(SMDPDL+RHOL*GRAT*COSTHA)
      YPL(1) = 0.0
      YPLRO(1) = 0.0
      TAURAT(1) = 1.0
      EMNUL(1) =  0.0
      FYPL(1) = 1.0
      MP = M+1
      DO 1 I=2,MP
      YPL(I) = YPL(I-1) + DELYPL
      YPLRO(I) = YPL(I)/ROPLUS
      TAURAT(I) = (1.0 + DUMP1*(2.0*YPLRO(I)-YPLRO(I)*YPLRO(I)))/(1.0 -
     1  YPLRO(I))
      IF (TAURAT(I)) 200,200,250
200   GO TO (300,400),IEMNU
300   EMNUL(I) = 0.0
```

```
      FYPL(I) = TAURAT(I)
      GO TO 1
250   EMNUL(I) = .5*(-1. + SQRTF(1.0 + 4.0*TAURAT(I)*(VDK*YPL(I)*(1.0 -
     1 EXPF(-YPL(I)/APLUS)))**2))
      GO TO (410,420), IEMNU
420   IF (EMNUL(I) - EMNUL(I-1)) 400,400,410
400   EMNULM = EMNUL(I-1)
      EMNUL(I) = EMNULM
410   FYPL(I) = TAURAT(I)/(1.0 + EMNUL(I))
 1    CONTINUE
      UPL(1) = 0.0
      GYPL(1) = 0.0
      DO 2 I=1,N
      J = 2*I
      JM = J-1
      JP = J+1
      DLUPLL = DELYPL/12.*(5.0*FYPL(JM) + 8.0*FYPL(J) - FYPL(JP))
      DLUPLR = DELYPL/12.*(-FYPL(JM) + 8.0*FYPL(J) + 5.0*FYPL(JP))
      UPL(J) = UPL(JM) + DLUPLL
      UPL(JP) = UPL(J) + DLUPLR
      GYPL(J) = UPL(J)*(ROPLUS - YPL(J))
      GYPL(JP) = UPL(JP)*(ROPLUS - YPL(JP))
      GYPL(J) = ABSF(GYPL(J))
      GYPL(JP) = ABSF(GYPL(JP))
 2    CONTINUE
      WL = 0.0
      DO 3 I=1,N
      M = 2*I
      MP = M + 1
      MM = M - 1
      DELWL = DELYPL/3.0*(GYPL(MM) + 4.0*GYPL(M) + GYPL(MP))*B
      WL = WL + DELWL
 3    CONTINUE
      FWFLOL = WL
      L = L + 1
      OWTL(L) = WL
```

```
    4  ORL(L) = RL
       RETURN
       END
CSRLLM
       SUBROUTINE  SRLLM
      COMMON  BLK,ANS,RES,CAL
      EQUIVALENCE   (BLK( 1),TSAT  ),(BLK( 2),PSAT  ),(BLK( 3),RO    ),
     1              (BLK( 4),WTOT  ),(BLK( 5),X     ),(BLK( 6),QO    ),
     2              (BLK( 7),DPDLFR),(BLK( 8),GRAT  ),(BLK( 9),COSTHA),
     3              (BLK(10),VISCL ),(BLK(11),VISCG ),(BLK(12),CPL   ),
     4              (BLK(13),ZAMBDA),(BLK(14),ZKL   ),(BLK(15),RHOL  ),
     5              (BLK(16),RHOG  ),(BLK(17),ZMOL  ),(BLK(18),SIGMA ),
     6              (BLK(19),CONAL1),(BLK(20),CONAL2),(BLK(21),TOL1  ),
     7              (BLK(22),TOL2  )
      EQUIVALENCE   (ANS( 1),DELTA ),(ANS( 2),ETA   ),(ANS( 3),H     ),
     1              (ANS( 4),HFILM ),(ANS( 5),HINT  ),(ANS( 6),TWSRJ ),
     2              (ANS( 7),TWNSRJ),(ANS( 8),TINT  ),(ANS( 9),SMDPDL),
     3              (ANS(10),OFR   ),(ANS(11),DPDLSH),(ANS(12),DPDLM ),
     4              (ANS(13),DPDLML),(ANS(14),DPDLMG),(ANS(15),REL   ),
     5              (ANS(16),REG   ),(ANS(17),VSTAR ),(ANS(18),RL    ),
     6              (ANS(19),RLLM  ),(ANS(20),WFLOL )
      EQUIVALENCE(RES(    1),YPLRO),(RES(1001),Y     ),(RES(2001),YPL   ),
     1           (RES(3001),TPL   ),(RES(4001),UPL   ),(RES(5001),ALPHA),
     2           (RES(6001),EMNUL),(RES(7001),TAURAT),(RES(8001),ORL   ),
     3           (RES(8201),OWTL  ),(RES(8401),ABUPL),(RES(9401),ABTAUR)
      EQUIVALENCE   (CAL(    1),FYPL),(CAL(1001),GYPL),(CAL(2001),ZYP  ),
     1              (CAL(3001),CX   ),(CAL(3002),PRL ),(CAL(3003),DXDL ),
     2              (CAL(3004),PI   ),(CAL(3005),N   ),(CAL(3006),L    ),
     3              (CAL(3007),M    ),(CAL(3008),NOIT),(CAL(3009),IEMNU)
      DIMENSION  YPLRO (1000),Y      (1000),YPL   (1000),TPL    (1000),
     1           UPL   (1000),ALPHA  (1000),EMNUL (1000),TAURAT (1000),
     2           ORL   ( 200),OWTL   ( 200),FYPL  (1000),GYPL   (1000),
     3           ZYP   (1000),BLK    (  22),ANS   (  20),RES   (10400),
     4           CAL   (3009),HOLL   (  14),ABUPL (1000),ABTAUR (1000)
       VRAT = VISCL/VISCG
       RORATH = (RHOG/RHOL)**.5
```

```
      IF (REG - 1000.) 1,2,2
    1 IF (REL - 1000.) 3,4,4
    2 IF (REL - 1000.) 5,6,6
    3 CX = VRAT*RORATH*(REL/REG)**.5
      GO TO 7
    4 CX = RORATH/18.65*VRAT*REL**.9/REG**.5
      GO TO 7
    5 CX = 18.65*RORATH*VRAT*REL**.5/REG**.9
      GO TO 7
    6 CX = VRAT*(REL/REG)**.9*RORATH
    7 RLLM = .299*CX**.756/(1.0 + .299*CX**.756)
      RETURN
      END
CSDPDLM
      SUBROUTINE  SDPDLM
     COMMON  BLK,ANS,RES,CAL
     EQUIVALENCE   (BLK( 1),TSAT  ),(BLK( 2),PSAT   ),(BLK( 3),RO     ),
      1            (BLK( 4),WTOT  ),(BLK( 5),X      ),(BLK( 6),QO     ),
      2            (BLK( 7),DPDLFR),(BLK( 8),GRAT   ),(BLK( 9),COSTHA),
      3            (BLK(10),VISCL ),(BLK(11),VISCG  ),(BLK(12),CPL    ),
      4            (BLK(13),ZAMBDA),(BLK(14),ZKL    ),(BLK(15),RHOL   ),
      5            (BLK(16),RHOG  ),(BLK(17),ZMOL   ),(BLK(18),SIGMA  ),
      6            (BLK(19),CONAL1),(BLK(20),CONAL2),(BLK(21),TOL1   ),
      7            (BLK(22),TOL2  )
     EQUIVALENCE   (ANS( 1),DELTA ),(ANS( 2),ETA    ),(ANS( 3),H      ),
      1            (ANS( 4),HFILM ),(ANS( 5),HINT   ),(ANS( 6),TWSRJ  ),
      2            (ANS( 7),TWNSRJ),(ANS( 8),TINT   ),(ANS( 9),SMDPDL),
      3            (ANS(10),OFR   ),(ANS(11),DPDLSH),(ANS(12),DPDLM  ),
      4            (ANS(13),DPDLML),(ANS(14),DPDLMG),(ANS(15),REL    ),
      5            (ANS(16),REG   ),(ANS(17),VSTAR ),(ANS(18),RL     ),
      6            (ANS(19),RLLM  ),(ANS(20),WFLOL )
     EQUIVALENCE(RES(   1),YPLRO),(RES(1001),Y     ),(RES(2001),YPL   ),
      1          (RES(3001),TPL   ),(RES(4001),UPL   ),(RES(5001),ALPHA),
      2          (RES(6001),EMNUL),(RES(7001),TAURAT),(RES(8001),ORL   ),
      3          (RES(8201),OWTL  ),(RES(8401),ABUPL),(RES(9401),ABTAUR)
     EQUIVALENCE   (CAL(   1),FYPL),(CAL(1001),GYPL),(CAL(2001),ZYP   ),
```

```
     1          (CAL(3001),CX   ),(CAL(3002),PRL ),(CAL(3003),DXDL  ),
     2          (CAL(3004),PI   ),(CAL(3005),N   ),(CAL(3006),L     ),
     3          (CAL(3007),M    ),(CAL(3008),NOIT),(CAL(3009),IEMNU)
      DIMENSION YPLRO (1000),Y      (1000),YPL    (1000),TPL     (1000),
     1          UPL   (1000),ALPHA  (1000),EMNUL  (1000),TAURAT  (1000),
     2          ORL   ( 200),OWTL   ( 200),FYPL   (1000),GYPL    (1000),
     3          ZYP   (1000),BLK    (   22),ANS   (   20),RES  (10400),
     4          CAL   (3009),HOLL   (   14),ABUPL (1000),ABTAUR (1000)
      GCH = 32.17405 * 1.296E7
      VRAT = VISCL/VISCG
      RHORAT = RHOG/RHOL
      ONEMX = 1.0 - X
      ATOT = PI*RO*RO
      DUM1 =1.0+.299*CX**.756
      DUM2 =DUM1*DUM1
      DRLDCX = .226/CX**.244/DUM2
      IF(REG - 1000.) 1,2,2
    1 IF(REL - 1000.) 3,4,4
    2 IF(REL - 1000.) 5,6,6
    3 DCXDX = -(RHORAT * VRAT * X / ONEMX)**.5/X/X/2.0
      GO TO 7
    4 DUM3 = (.4*X + .5)/(X**1.5 * ONEMX**.5)
      DCXDX = -REL**.4/18.65*(RHORAT*VRAT)**.5*DUM3
      GO TO 7
    5 DUM3 = (.9 - .4*X)/X**1.5/ONEMX**.5
      DCXDX = -18.65/REG**.4*(RHORAT*VRAT)**.5*DUM3
      GO TO 7
    6 DCXDX = -.9/X**1.9*RHORAT**.5*(VRAT/ONEMX)**.1
    7 DRLDX = DRLDCX*DCXDX
      GTSXL = WTOT/ATOT * WTOT/ATOT * DXDL / GCH
      DUMP4 = DRLDX*(ONEMX/RL)**2 + 2.0*ONEMX/RL
      DPDLML = -GTSXL/RHOL*DUMP4
      DUMP5 = DRLDX*(X/(1.0-RL))**2 + 2.0*X/(1.0 - RL)
      DPDLMG = GTSXL/RHOG*DUMP5
    8 DPDLM = DPDLML + DPDLMG
      RETURN
```

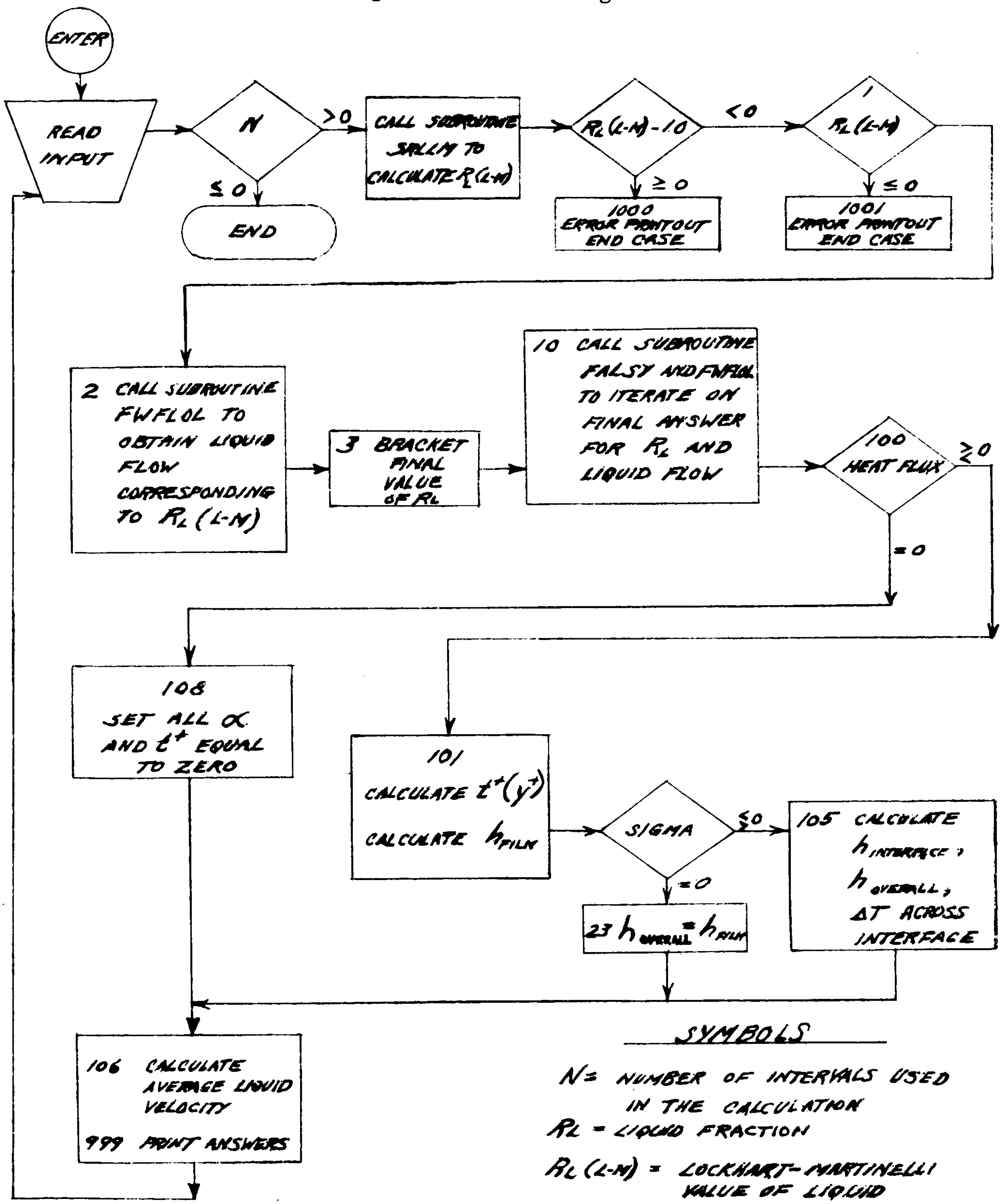
```
      END
CFALSY
      FUNCTION FALSY(AXR,XL,XR,E,R,L,YY)
      NN = 2
            XP = XL
           XPP = XR
            RR = R
            EP = E*3.
             J = 0
    5       F1 = AXR(XP)
            F2 = AXR(XPP)
      IF(R-F1)7,8,7
    8       XX = XP
      GO TO 135
    7 IF(R-F2)6,9,6
    9       XX = XPP
      GO TO 135
    6       XO = (XP*(F2-RR)-XPP*(F1-RR))/(F2-F1)
            YO = AXR(XO)
        XS1P2 = (XO*(F2-RR)-XPP*(YO-RR))/(F2-YO)
        XS1P1 = (XO*(F1-RR)-XP*(YO-RR))/(F1-YO)
   30 IF(ABSF((XS1P2-XS1P1)/(XS1P2+XS1P1))-.000005 )35,35,10
   35       XX = (XS1P2+XS1P1)/2.
      GO TO 135
   10        N = 0
            GA = XS1P1
   15 IF(GA-XP)100,100,20
   20 IF(GA-XPP)25,100,100
   25       Y2 = AXR(GA)
   45 IF( F1      -RR)60,50,70
   70 IF(Y2-RR)80,55,90
   50       XX = XP
         FALSY = XX
           YZY = F1
      GO TO 136
   60 IF(Y2-RR)90,55,80
   55       XX = GA
         FALSY = XX
           YZY = Y2
```

```
      GO TO 136
 80       XPP = GA
           F2 = Y2
      GO TO 100
 90        XP = GA
           F1 = Y2
100   IF(N)110,95,110
 95         N = 1
           GA = XS1P2
      GO TO 15
110   IF(ABSF(  (XPP-XP)/(XPP+XP))-EP)130,130,115
115   IF(J-30)120,125,125
120         J = J+1
      GO TO 6
125   WRITE OUTPUT TAPE NN,126,XP,XPP,F1,F2
126   FORMAT(10X46HTHE METHOD OF FALSE POSITION FAILED TO ITERATE 3HXP=F
     112.8,4HXPP=F12.8,3HF1=F12.8,3HF2=F12.8)
140         L = J
      RETURN
130        XX = (XP*(F2-RR)-XPP*(F1-RR))/(F2-F1)
135     FALSY = XX
          YZY = AXR(XX)
136        YY = YZY
      GO TO 140
      END
```

APPENDIX E

Computer Flow Diagrams

Flow Diagram for Main Program



SYMBOLS

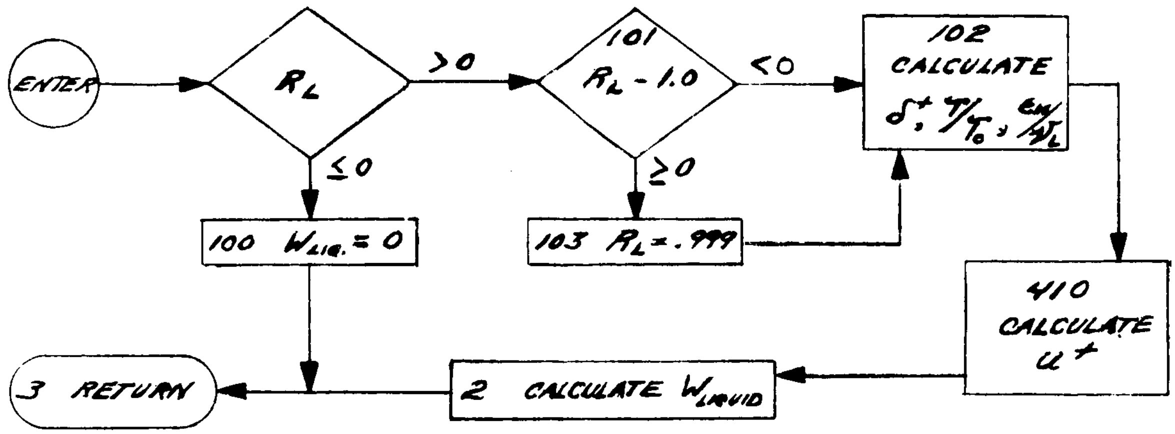
N = NUMBER OF INTERVALS USED IN THE CALCULATION

R_L = LIQUID FRACTION

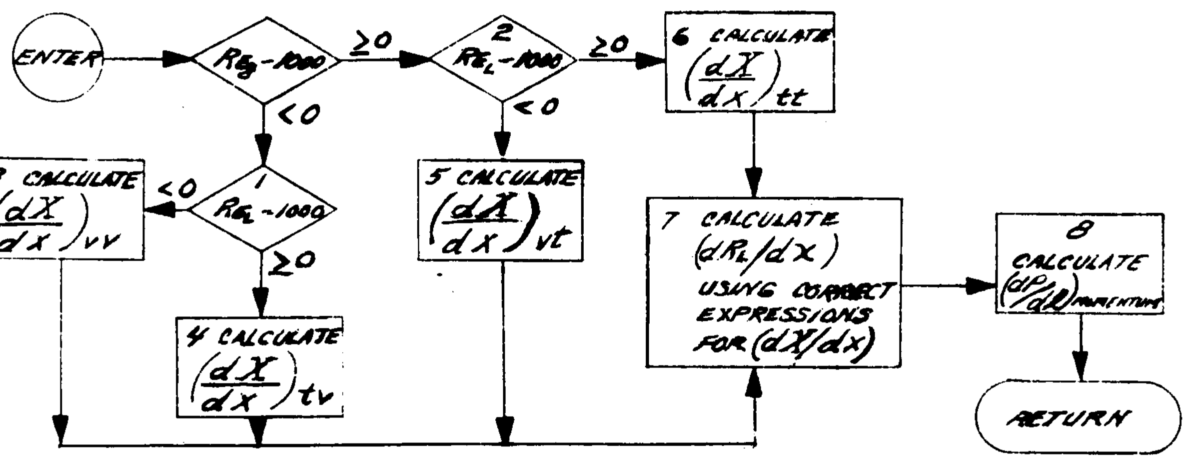
R_L (L-M) = LOCKHART-MARTINELLI VALUE OF LIQUID FRACTION

Flow Diagrams for Program Subroutines

Subroutine FWFLOL



Subroutine SDPDLM



Subroutine SRLLM