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Mathematical model of temperature profiles and coking in a crude oil heater tube

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ABSTRACT

Title of Thesis:
Mathematical Model of Temperature Profiles and
Coking in a Crude Oil Heater Tube

Joseph C. Polimeni
Master of Science in Chemical Engineering, 1983

Thesis directed by:
Dr. Gordon Lewandowski
Professor of Chemical Engineering

A mathematical model to predict temperature profiles and coking of crude oil in furnace tubes is presented. The model assumes that the coking mechanism is due to a reaction in the laminar sublayer, whose rate depends upon the temperature profile. That profile is obtained by a numerical solution of the appropriate transport equations, with velocity profiles that may be laminar or turbulent, and including the temperature dependence of the crude oil properties. In addition, velocity and temperature profiles were adjusted when necessary to ensure closure of the heat and material balances. As a by-product of this study, a correction was found necessary to Nikuradse's formulation of the turbulent velocity profile in order to ensure material balance closure. Comparisons are shown between the model and the limited published data.

MATHEMATICAL MODEL OF TEMPERATURE PROFILES AND COKING IN A CRUDE OIL HEATER TUBE

by
Joseph C. Polimeni

Thesis submitted to the Faculty of the Graduate School of the New Jersey Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering
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APPROVAL SHEET

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Mathematical Model of Temperature Profiles and Coking in a Crude Oil Heater Tube

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I. Introduction

Furnaces used to heat crude oil consist of banks of alloy steel tubes. The heat is transferred from the flame to the tubes by radiation and convection. During furnace operation, a layer of coke is formed on the inside of the tube walls. The thickness of this coke layer increases with time, and thereby increases the resistance to heat transfer across the tube wall. The increased resistance has two undesirable effects. First, in order to maintain a constant heat transfer rate, the outside tube wall temperature must increase (by increasing the furnace firing rate). Eventually (without decoking) the tube wall reaches the failure point, bulges, and ruptures. Secondly, there is a reduction of the radiant section efficiency. Much of the extra energy leaving the radient section can be recovered in the convection section, but this shift leads to further fouling of the convection tube bank and results in even further decreases in overall efficiency (1). Since furnaces and steam boilers consume approximately 75% of the energy used at petroleum refineries (2) coking can be a costly problem.

In addition, coking would clearly be a significant problem to overcome if synthetic fuels are processed. Fuels produced synthetically from coal contain a larger amount of aromatics and have a lower hydrogen to carbon atomic ratio (3). Both of these conditions make oil from coal more inclined to coking than conventional petroleum crude (4).

In order to assess the current state-of-the art regarding coking predictive techniques, and to establish a data base, a thorough literature search was performed using the following computer data bases:

COMPENDEX-A machine readable version of "The Engineering Index" which provides abstracted information from the world's significant engineering and technological literature. The database contains all the information in the Engineering Index since 1970.

FLUIDEX-A specialized database produced by the British Hydromechanics Research Association (BHRA). The database contains records from 1974 to present.

DISSERTATION INDEX-A database which contains the subject, title, and author of virtually every American dissertation accepted at an accredited institution since 1861. Approximately 99% of all American dissertations are cited in this file. Masters thesis have been included since 1962.

The Dialog corporation allows searches through these databases. Key words are checked against each entries abstracts and classifications.

The following combinations of keywords were searched for in Compendex:

Coke or Coking and Reaction Kinetics

Coke or Coking and Mathematical models

Coke or Coking and Kinetics and Pyrolysis

Coke or Coking and Cracking and Naphthas

Naphthas and Cracking

Naphthas and Pyrolysis

Pyrolysis and Mathematical Models

Crude Oil and Mass Transfer

Petroleum and Mass Transfer

Temperature Profile and Turbulent Flow

Coking and Scale Formation (which turned out to be the most useful key words)

Furthermore every article in the Oil and Gas Journal, Hydrocarbon Processing, and CEP which delt with coke or coking since 1970 was checked.

The BHRA index was checked for:

Coke or Coking

Temperature Profile and Turbulent Flow

The Dissertation index was checked for:

Coke or Coking and Mathematical Model

In addition to these searches which I performed myself, I contracted the Engineering Societies Library and the NJIT Library to do a literature search coking of crude oils and no additional information was found.

Industry, while recognizing the importance of coking on the economics of design and operation of furnaces, is usually satisfied with the use of estimated values of coking obtained from plant data (which is proprietary). Design equations which account for coking generally include an empirical fouling factor as part of the heat transfer coefficient (1). Although a better understanding of coking could be economically important, there exist no models to predict coking from a theoretical basis, and only one empirical model.

A. Coking from Gas Phase Reactions

Previous studies on coking have been mainly concerned with gas phase reactions, specifically the cracking of naphtha to produce ethylene. Although the coking of crude oil is not the same as coking of naphtha, some of the parameters which affect gas phase coking may also affect liquid phase coking.

Coke formation from a gas phase reaction is a combination of hetergeneous surface reactions (catalytic) and homogeneous gas phase reactions (5,6). The surface reaction is strongly dependent on the surface condition, which is a function of the bare metal composition, as well as the composition of reaction products that accumulate at the tube surface. These reaction products may be the result of inorganic reactions between the metal and gas constituents (such as water vapor, hydrogen sulfide, etc.), or the reaction products may include coke formation. If the hydrocarbon is relatively ash free, then the deposited coke should be low in metal content, and therefore inert. As such a layer covers the more catalytically active metal tube wall, reaction rates would decline. This has been observed in lab experiments by Albright & Tsai (5) and Newsome (7). However, in an industrial situation the hydrocarbon ash content may be significant, particularly when crude oil is involved. Therefore, the coke deposit may bring with it to the tube surface significant amounts of metal species. In that case, the coke deposit may actually enhance the reaction rate, and this has been observed by Scarborough (8).

Different feed stocks display different coking rates (7). Certain unsaturated hydrocarbons have been found to be precursors; including acetylenic compounds, olefins, and aromatics (5). Coking also increases with the carbon-to-hydrogen ratio (9).

In metal tubes, steam decreases the coking tendency of naphtha (7). This may be due to a reduction of the naphtha partial pressure, as well as oxidation of the coke. However, when a Vycor glass tube is used, steam has little effect on the coking rate (10).

Surface reactions are always decreased when hydrogen sulfide is used to pretreat the furnace tubes. However hydrogen sulfide is highly corrosive, especially at high temperatures (10).

Chen and Maddock (6) have derived a gas phase coking model which assumes that the coke formation reaction is essentially the cracking of hydrocarbons into coke at the tube wall surface. The coke precursors travel from the bulk of the process gas to the wall surface. At low temperatures, the overall coking rate is kinetically controlled and would be dependent upon the tube wall temperature. At temperatures above 850 C (temperatures of practical cracking operation), the coking rate is mass transfer controlled and proportional to the mass transfer coefficient. They propose that the coking rate may be determined as a function of Reynolds number and tube diameter using a j-factor analogy for mass transfer.

Fernandez-Baujin and Solomon (11) propose an empirical equation to predict the coking rate, which assumes a two-step mechanism:

1. Mass transfer of coke precursors from the bulk of the gas to the walls of the tube.

2. Chemical reaction of coke precursors at the tube wall resulting in the formation and deposition of coke.

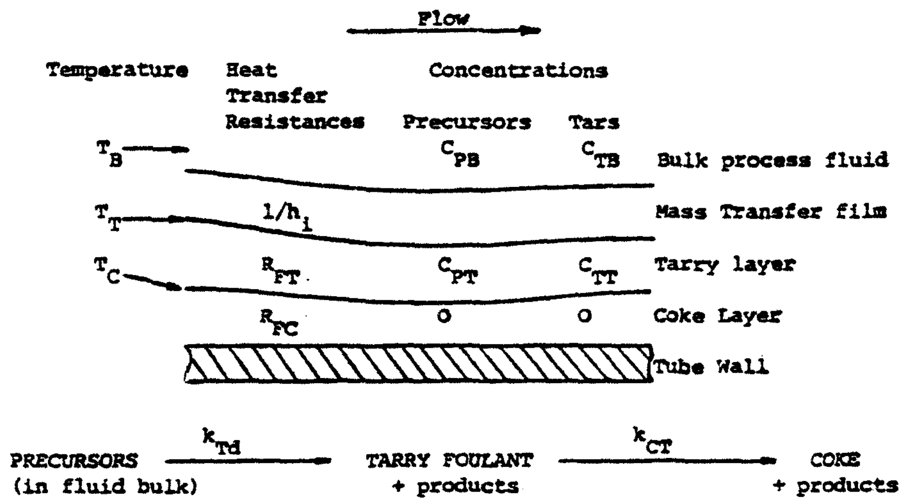
In gas phase coking it has been observed that there is a decrease in coking with an increase in mass flow rate, this may be explained by assuming that the coke is produced in the laminar region near the tube wall. The temperature in this layer is higher than the bulk temperature and hence the coking rate is high in this region. The conversion of coke precursors to coke in this region is called the film effect. Coking in small tubes and low mass velocities is primarily due to the film effect, while coking at high mass velocities is mainly due to high tube wall temperatures (12).

B. Coking from Crude Oil

A thorough literature search revealed that only Crittenden (1979) and Scarborough et al. (1979) have attempted to develop a method to predict the amount of coke obtained when heating crude oil.

1. Model of Crittenden and Kolaczkowski (1)

Crittenden and Kolaczkowski developed a coking model by combining empirical relationships which are used to predict fouling in heat transfer equipment with a two-step kinetic model for coking. The equations are based upon the following schematic:



The tarry layer is where the coke precursors react and where tars and asphaltenes may diffuse back into the bulk fluid. Fluid shear in the tarry layer can also remove coke from the wall.

The deposition of the tarry layer is primarily kinetically controlled, not mass transfer controlled. The reaction order of the coking process is unknown so it was assumed that the reaction is pseudo-first order. They also assumed that the rate constant accounts for the mass transfer of the precursors from the bulk to the tarry layer. The conversion of the tarry layer to coke is also considered to be a first order reaction. The temperature dependence of these reactions is assumed to be represented by the Arrhenius equation. Crittenden, however, does not mention how to obtain the temperatures of the coke and tarry layers.

Coke removal by fluid shear is assumed to be linear with shear stress, as first proposed by Kern and Seaton in 1959.

The mass transfer terms for the coke precursors (which are not identified) are expressed by a j-factor analogy.

The final model contains seven constants which must be determined from data. None of the seven constants directly account for the type of oil, which would certainly affect the coking rate.

Crittenden could not find any published data on coking of crude oil, so he attempted to prove the validity of his equation by using gas oil data from Watkinson (13).

Watkinson's data was from gas oil at low temperatures (300 F), not crude oil at high temperatures. The substance Watkinson observed on the inside of the tube walls was soft and sooty, not hard like coke. Watkinson recirculated the gas oil and Crittenden's model clearly assumes the oil is once-through. Finally, Watkinson used a tube that was only 0.359 inch i.d., as compared to the 6 inch i.d. used in commercial heaters.

Watkinson found that the accumulation of coke stopped after a few days although there were still particulates in the oil. However, particulates do not solely contribute to coking. The presence of polycyclic aromatics, which are known coke precursors, were not tested for.

Crittenden reports good agreement between his equation and the Watkinson data. This would actually seem to bring doubt on the validity of Crittenden's model, although with seven empirical constants the model may be able to fit almost any data.

2. Data of Scarborough et.al. (14)

Published data on coking of crude oil in furnace tubes is scarce. Apparently the only published data is by Scarborough et.al. who were attempting to establish empirically the relative rate of coke deposition as a function of bulk temperature, heat flux, mass velocity, and film temperature. These data were used to check the validity of the model presented in this paper. Therefore, an overview of the limitations and inconsistencies in their data follows.

The apparatus they used consisted of 304 stainless steel tubes .591 inches in diameter and 9 feet long. By comparison, industrial furnace tubes are usually 6 inches in diameter and at least 40 feet long (15). Although the results could be scaled up to industrial size, the actual scale-up factor is unknown, since the effect of the L/D ratio on coking is unknown. The length is much too short to comfortably neglect end-effects, and to study the pattern of coking downstream as compared to upstream.

The crude oil entered each tube at approximately 650 F, as a slip stream from a refinery. The slip stream was assumed to be of constant quality. However, the type of crude oil used was not reported. Each type of crude oil has a different amount of coke precursors, and therefore different types of crude oil will coke differently. In order to ensure single-phase (liquid) flow, they used booster pumps. However, the actual slip stream has two phase (gas/liquid) flow.

The experiments were conducted in order to obtain relative coking rates, and therefore their data is insufficient for a proper mathematical model. Pressure drop, actual coke thickness as a function of length of the tube, and tube wall temperature for each thermocouple were not presented.

In order to better obtain the rate of coking, the amount of coke which is carried downstream should also have been determined, but was not.

The investigators reported most of the data in terms of thermal resistance and not coke thickness. They determined the thermal resistance by using the following equation:

$$\text{Thermal Resistance} = \frac{(\text{Thermocouple Temp}) - \text{Bulk Temp}}{(\text{Heat Flux})(\text{Area})}$$

The equation is valid if you measure the bulk temperature. However, the bulk temperature was not measured. A listing of their computer program reveals that they assumed a linear bulk temperature profile based upon the inlet and outlet temperatures. The bulk temperature may not follow a linear profile (as my model indicates: see Figure 47), and therefore the values of thermal resistance they report may be in error. This may also be the reason why one data set had an increase in thermal resistance but no reported coke (14).

The actual coke thickness is a function of tube length, which would be very important for a coking model, but was only reported for one case. The coke thickness at the end of each experiment was reported as a range, which was generally equivalent to the average value $\pm$100%.

Each tube was surrounded by an electrically heated furnace, which was to provide a constant heat flux. The investigators connected thermocouples to the experimental tube at one foot increments. They did not mention, however, whether the thermocouples were inside the wall of the tube, or if the thermocouples were at the inside surface of the tube. The tube metal temperatures reported are only given at two of the 9 thermocouple positions and only given for some of the data.

Although the investigators report the bulk temperature measured at the inlet of the tube to be essentially constant, a set of sample data presented in one of their reports (16) shows considerable variations in the outlet bulk temperature. For a reported outlet bulk temperature of 684 F, the outlet temperature actually varied from 436 F to 715 F. The oscillation could have been due to the process controller they used (Leeds Northrop), since they reported having quite a bit of trouble with the controller (17). This is an indication that the heat flux was not constant.

There are some anomalous data reported. Since the heat flux was to be constant, and crude oil was being heated, it is impossible for the tube metal temperature to decrease downstream, yet two reported cases showed this type of behavior. They did report having trouble supplying power to the heaters (18) and perhaps this was the cause of the anomalous behavior.

Some further anomalous behavior can be shown by comparing the data in Table 1:

TABLE 1: ANOMALOUS SCARBOROUGH DATA

Data Number	D2	D3	C2	C3	
Flow Rate	143	143	285	285	lbm/ft2-sec
Temperature in	650	640	660	645	F
Heat flux	56	45	59	44	kBtu/hr-ft2
Tube Metal Temp. (at thermocouple 3 at initial time)	865	910	800	860	F

Clearly this data is inconsistent, the initial tube metal temperature for D2 cannot be less than D3, and the initial tube metal temperature for C2 cannot be less than C3.

They report a relationship between mass velocity, coking rate, and film temperature in the form of thermal resistance increases which they display in a figure. The figure, shown below, has very scattered data, and the lines drawn through the data were clearly not fit with least squares. By replotting the data and using least squares the correct relationship is shown in Figure 1a. Notice, for example, the relationship presented by the investigators for a flow rate of 450lbm/sec-ft2. There are two points present and instead of drawing a straight line

FIGURE 1a: RESULTS FROM SCARBOROUGH REPLOTTED

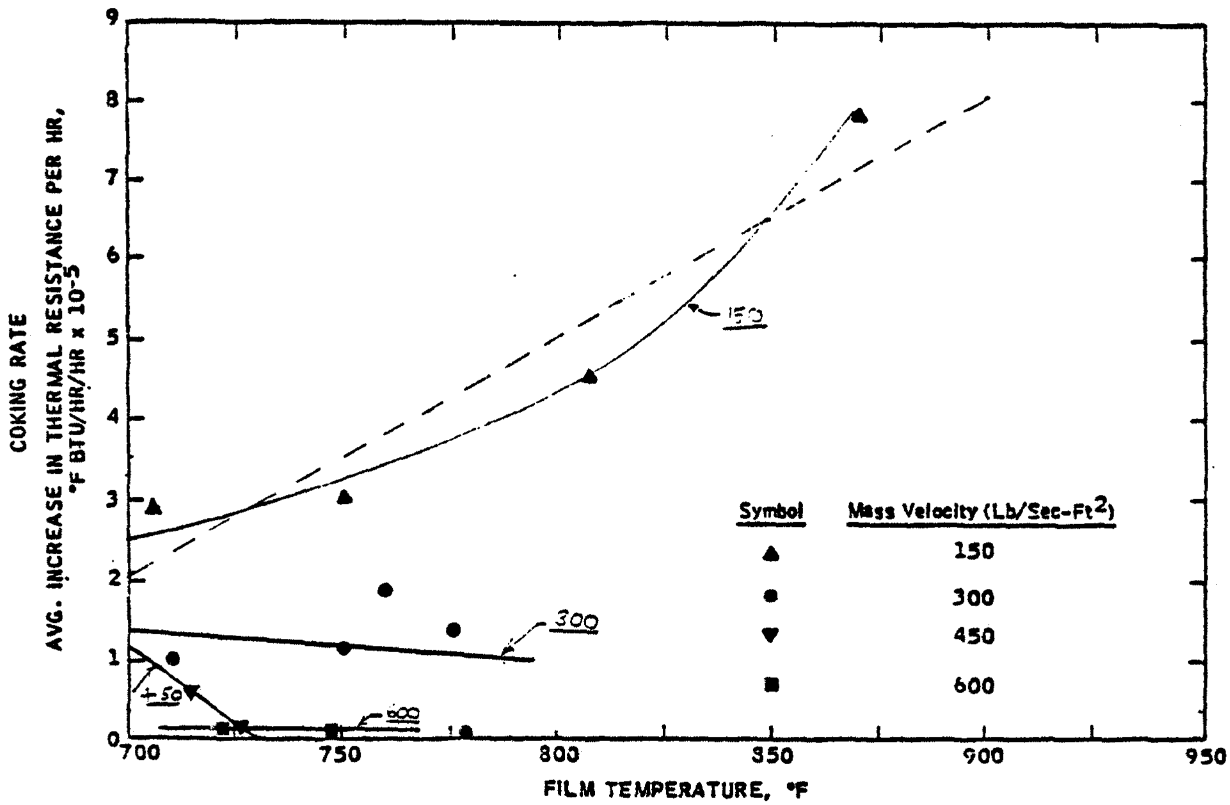
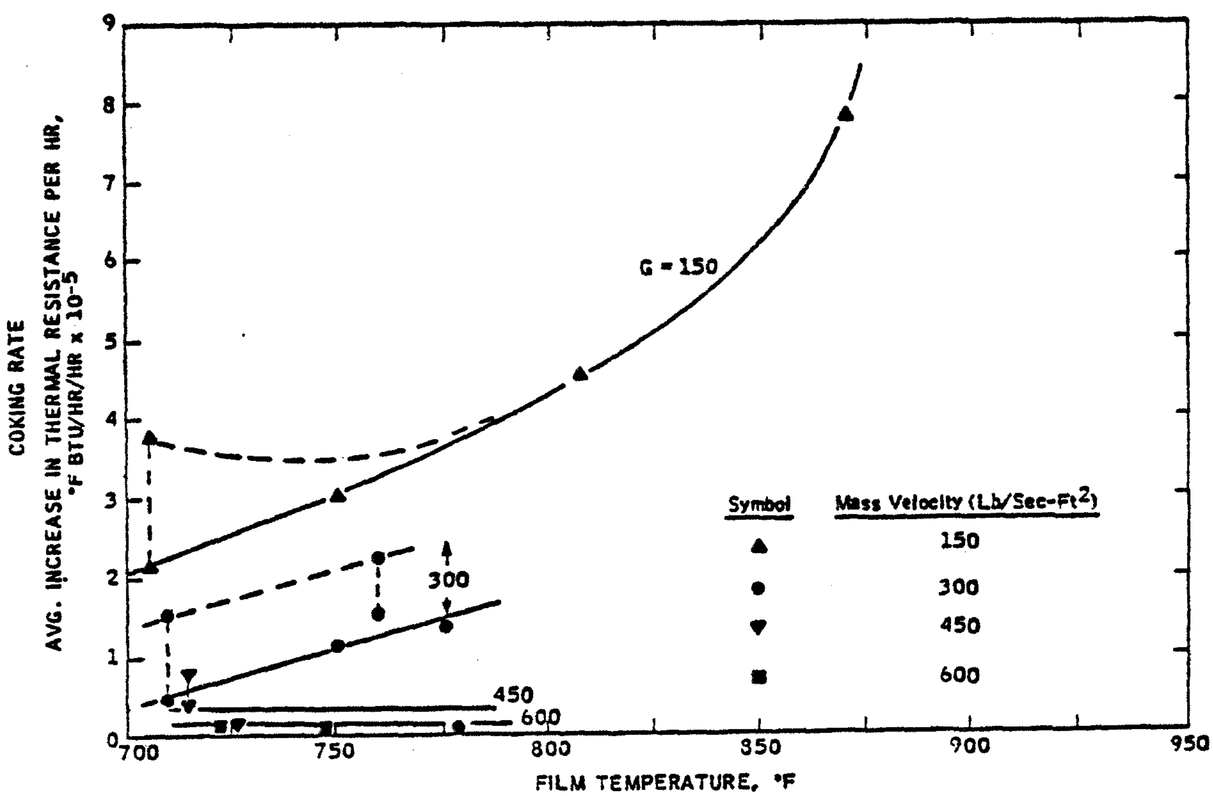


FIGURE 1b PLOT FROM SCARBOROUGH



connecting the two points the investigators drew a horizontal line between the two points (Figure 1b). Also note that they do not report how they have determined the film temperature. Most likely they used a film coefficient, which is not accurately known. The data for a mass flow rate of 150 lbm/s-ft2 has been replotted two ways (Figure 1a). The solid line indicates a least squares fit with an Arrhenius-type equation, while the dotted line is a straight line fit with least squares.

C. Physical Properties of Crude Oil

Crude oil is a complex mixture of many different hydrocarbons. The distribution of the hydrocarbons varies with the source of the oil. Determining the actual composition of a particular crude oil is a formidable task. Therefore, crude oil is typed with a characterization factor which is based on the average molal boiling point and API gravity. Typically a high characterization factor (around 14) indicates a mixture of low molecular weight hydrocarbons, and a low characterization factor (around 10) indicates a mixture of high molecular weight hydrocarbons.

Viscosity may be expressed as a logarithmic function of temperature (17):

$$\nu = A\, e^{(B/T)}$$

where: ν = kinematic viscosity (μ/ρ), centistokes

T = absolute temperature, K

$$A = (91.836\ Tb^{-1.75} - 29.263)(C/(B*1.E6))$$

$$B = e^{(4.717 + 0.00526\ Tb)}$$

Tb = mid-boiling temperature of crude, K

C = characterization factor, $\sqrt[3]{Tb}/Sg$ Tb, in R

Sg = specific gravity, $\dfrac{141.5}{API + 131.5}$

API = API gravity

The average percent deviation from the actual viscosity is approximately ten percent.

Thermal conductivity and heat capacity of crude oil are linearly dependent upon API gravity and temperature. A correlation of the data in Nelson (20) has resulted in the following equations:

$$Cp = 3.35 \times 10^{-1} + 2.16 \times 10^{-3} (API) + 5.87 \times 10^{-4} (T)$$

$$k = 6.48 + 0.0455 (API) - 0.00237 (T)$$

where: Cp = heat capacity, BTU/lbm-F

k = thermal conductivity, 100 (BTU/hr-ft-F)

T = temperature, F

The density of crude oil can be represented by a nonlinear equation which depends upon API gravity and temperature. By regressing the data in Nelson (21) the following equation resulted:

$$\rho = 62.22 + 97.25 \times 10^{-3} (API) - 204.2 \times 10^{-4} (API)^{2}$$
$$-94.67 \times 10^{-4} (T) - 83.61 \times 10^{-7} (T)^{2}$$

where: ρ = density, lbm/ft3

T = temperature, F

D. Thermal Conductivities of Stainless Steel and Coke

The following equation represents a linear fit to data (22) for the thermal conductivity of 304 stainless steel between 572 and 932 degrees F:

$$k = 8.52 + 4.17 \times 10^{-3} (T)$$

where: k = thermal conductivity, BTU/hr-ft-F

T = temperature, F

For the thermal conductivity of coke, the following data is taken from a figure presented by Scarborough et. al. (14):

Tube Position	Thermal Resistance F/BTU-hr x 1E-3	Coke Thickness inches
1	3.00	0.0022
2	4.06	0.0097
3	4.61	0.0120
4	5.06	0.0115
5	5.11	0.0151
6	5.28	0.0151
7	4.89	0.0138
8	4.28	0.0160

Using the equation:

$$\text{Thermal Resistance} = \frac{\text{Coke Thickness}}{\text{(Thermal Conductivity)(Area) of Coke}}$$

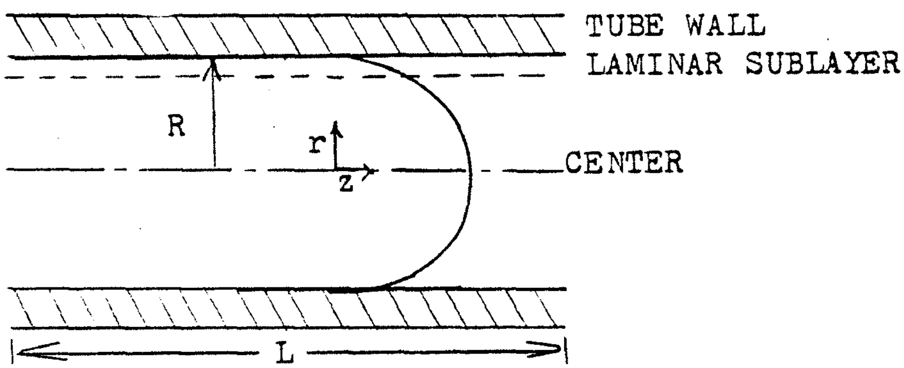
where area is the inside surface area of the tube (1.46 ft2) the thermal conductivity of coke at each tube position can be calculated:

Tube Position	Thermal Conductivity of Coke BTU/hr-ft-F
1	0.00423
2	0.1376
3	0.1485
4	0.1305
5	0.1688
6	0.1634
7	0.1609
8	0.2135
Average--------	0.1609

II. Mathematical Analysis

The rate of coking is a very strong function of temperature. Therefore, any coking model is only as good as the temperature profile used. Hence, a large portion of the present model is devoted to determine the temperature profiles for laminar and turbulent flow.

Consider a fluid flowing in a circular tube as shown below:



The following conditions will be imposed:

(1) Temperature is a function of r and z.

(2) The physical properties of the fluid:

ρ - density, lbm/ft3
k - thermal conductivity, BTU/hr-ft-F
Cp - heat capacity, BTU/lbm-F
μ - viscosity, lbm/s-ft

are dependent upon the bulk temperature of the fluid, and are therefore functions of z. (This means that velocity will also change with z.)

(3) The velocity profile is fully-developed (end effects are ignored).

(4) Material balance closure is insured by making $\rho\langle V_z\rangle$ equal to a constant.

(5) The fluid is Newtonian and incompressible.

(6) Viscous dissipation and axial conduction may be neglected in the energy balance.

(7) Although coke build-up is an unsteady-state phenomenon, we will consider a small time segment (Δt) over which steady-state balances may be written.

With these considerations, the energy equation in cylindrical coordinates reduces to:

$$\rho C_p V_z \frac{\partial T}{\partial Z} = k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right] \tag{1}$$

Letting

$$\alpha = \frac{k}{\rho C_p}$$

equation (1) becomes:

$$V_z \frac{\partial T}{\partial Z} = \alpha\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right] \tag{2}$$

A. <u>Laminar Flow</u>

For fully-developed laminar flow, Vz can be determined by the Hagen-Poiseuille equation:

$$V_Z = \frac{\Delta P R g_c}{4\mu L}\left[1-\left(\frac{r}{R}\right)^2\right] \tag{3}$$

This equation can be rewritten as:

$$V_Z = 2\langle V_Z\rangle\left[1-\left(\frac{r}{R}\right)^2\right] \tag{4}$$

where

$$\langle V_Z\rangle = \frac{\int_0^R V_Z\, r\, dr}{\int_0^R r\, dr} = \frac{\Delta P R^2 g_c}{8\mu L} \tag{5}$$

Equations (2), and (4) can then be used to determine the temperature profile.

B. <u>Turbulent Flow</u>

The empirical equations proposed by Nikuradse (23) for fully-developed turbulent flow are the ones chosen for this model. There are three equations proposed by Nikuradse. Each equation is applied in a different flow region.

The Nikuradse equations are:

$$\bar{V}_z = V^*(Y) \qquad (0 < Y < 5) \tag{6}$$

$$\bar{V}_z = V^*(5.0\ln(Y) - 3.05) \quad (5 < Y < 30) \tag{7}$$

$$\bar{V}_z = V^*(2.5\ln(Y) + 5.5) \quad (30 < Y) \tag{8}$$

where

$$Y = \frac{(R-r)\,V^*\rho}{\mu}\text{, dimensionless} \tag{9}$$

and

$$V^* = \sqrt{\frac{\tau_o}{\rho} g_c} \tag{10}$$

τ_o is the shear stress at the wall (24),

$$\tau_o = \frac{\Delta P\, R}{2\, L} \tag{11}$$

The tube is assumed to be horizontal so the gravity term is neglected.

$$\Delta P = \frac{\rho f L \langle V_Z \rangle^2}{r\, g_c} \tag{12}$$

$\langle V_Z \rangle$ is the average velocity

f is the Fanning friction factor

The Fanning friction factor may be estimated over a wide range of Reynolds numbers with the Round equation (25).

$$f = \frac{1}{4} \left\{ 1.8 \ln \left(\frac{N_{RE}}{1.35\, N_{RE}\left(\frac{\epsilon}{D}\right) + 65} \right) \right\}^{-2} \tag{13}$$

ϵ is the roughness factor, for commercial steel pipe the value is 0.00015 ft.

$$N_{RE} = \frac{D \langle V_Z \rangle \rho}{\mu} \tag{14}$$

therefore

$$V^* = \langle V_Z \rangle \sqrt{\frac{f}{2}} \tag{15}$$

and

$$\frac{V^*}{\langle V_Z \rangle} = \sqrt{\frac{f}{2}} \tag{16}$$

Once again, the average velocity $\langle Vz \rangle$ can be determined at any value of z by the integral:

$$\langle V_Z \rangle = \frac{\int_0^R V_Z\, r\, dr}{\int_0^R r\, dr} \tag{17}$$

The turbulent flow velocity profile includes eddies (26) which result in oscillations about the time-smoothed values. Following standard procedures (27), the turbulent energy flux is accounted for by assuming an eddy diffusivity for heat transfer (ϵ_H):

$$\bar{V}_z \frac{\partial \bar{T}}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\alpha + \epsilon_H\right)\frac{\partial \bar{T}}{\partial r}\right] \tag{18}$$

(where the superscript bar denotes time-smoothed values)

The Reynolds analogy states that the eddy diffusivity for heat transfer and momentum transfer are equal:

$$\epsilon_H = \epsilon_M \tag{19}$$

The eddy diffusivity for momentum transfer (ϵ_M) can be determined by the equation:

$$\epsilon_M = \ell^2 \left|\frac{\partial \bar{V}_z}{\partial r}\right| \tag{20}$$

The Prandtl mixing length (ℓ) can be approximated for the entire flow regime with the Van Driest Model (28):

$$\ell = (R - r)\,K\left[1 - \frac{\Gamma}{Y}\right] \tag{21}$$

where

Γ is the value of Y at the buffer layer-core interface. This value has been reported to be 26 (dimensionless).

K is an empirical proportionality factor (Deissler's constant), equal to 0.36 (dimensionless).

The thickness of the laminar sublayer (δ) has been estimated by Nikuradse (23) from the following equation:

$$Y = 5 = \delta \frac{V^* \rho}{\mu} \tag{22}$$

C. Transition Flow

As an additional assumption in the model, for the Reynolds' number range of 2000 to 4000, the velocity profile is determined by a linear combination of the laminar and turbulent profiles using Reynolds' number as the weighting factor:

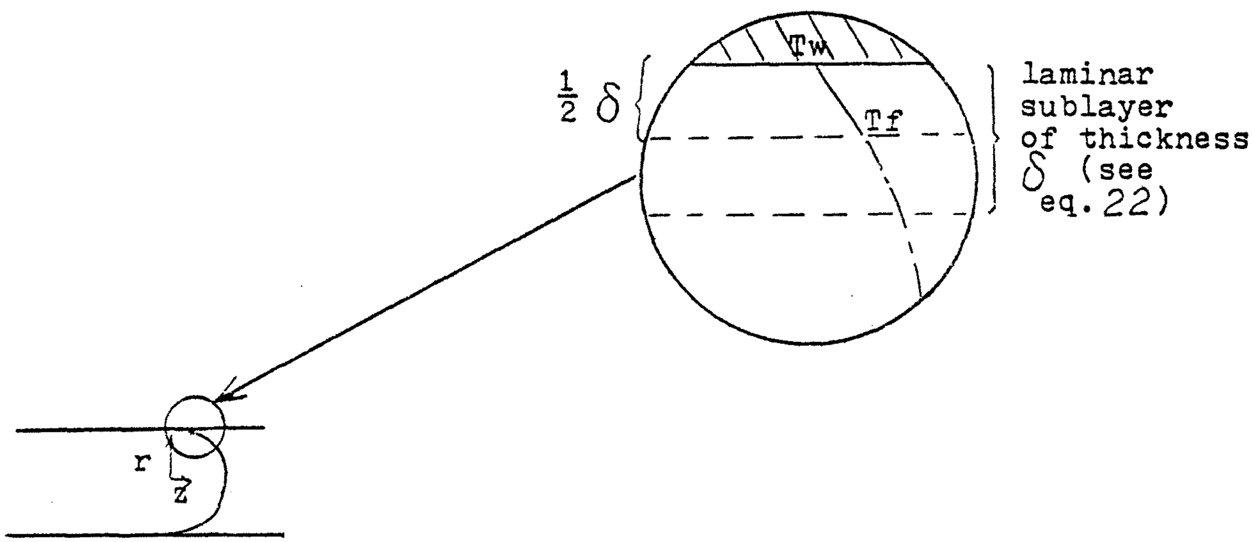
$$V_{z\,\text{transition}} = \left[\frac{4000 - N_{RE}}{2000}\right] V_{z\,\text{laminar}} + \left[\frac{N_{RE} - 2000}{2000}\right] \bar{V}_{z\,\text{turbulent}} \tag{23}$$

D. Bulk Temperature

The bulk temperature can be determined at any value of z (axial position) by the integral:

$$T_{\text{bulk}} = \frac{\int_0^R V_z\, T\, r\, dr}{\int_0^R V_z\, r\, dr} \tag{24}$$

E. Film Temperature



Assuming a linear temperature profile from the wall to one half the thickness of the laminar sublayer, a characteristic film temperature (Tf) can be calculated by:

$$T_f = \frac{\frac{\Delta q}{\Delta z}\left(\frac{\delta}{2}\right)}{2\pi R k} + T_W \tag{25}$$

$$\frac{\Delta q}{\Delta z} = m C_p \frac{\Delta T_{bulk}}{\Delta z} \tag{26}$$

where q = rate of heat transfer through the wall

m = the mass flow rate of the crude oil

Cp = the heat capacity of the crude oil

k = the thermal conductivity of the crude oil

ΔTbulk = change in bulk temperature over axial increment Δz

This definition of film temperature ensures closure of the energy balance.

F. Kinetic Rate Constant

The coking rate in the laminar sublayer was assumed to be zero order, with the kinetic rate constant determined from Scarborough's data (29):

Average Film Temperature (Degrees F)	Coking Rate (inches/hr)
898	1.75 E-04
888	1.55 E-04
809	5.50 E-05

These data are at the same linear velocity, and were fit to an Arrhenius expression (see Figure 2):

$$kc = 2797.7 \exp(-22518.3/Tf) \qquad (27)$$

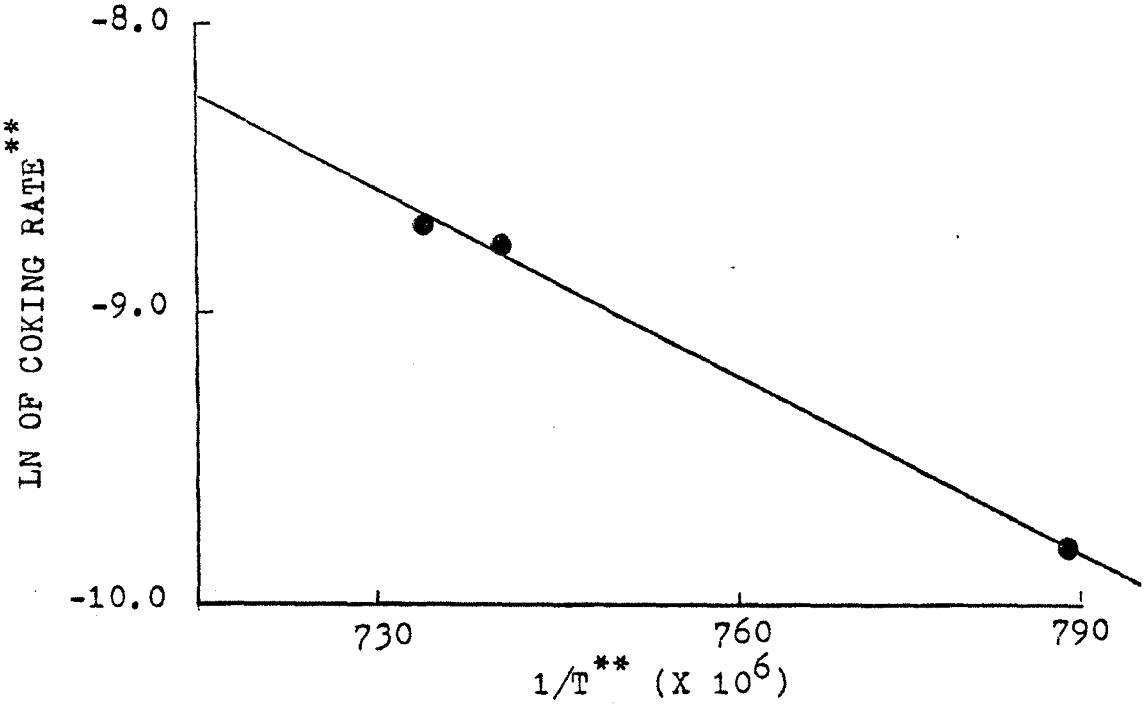
where Tf is the average film temperature in degrees Rankine.

and kc is the zero-order kinetic rate constant in inches/hr

22518.3 = E/R, and therefore the activation energy for coke formation (E) turns out to be 44743 BTU/lb-mole (or 24.85 kcal/gmole).

Note, however, that this correlation is heavily dependent on the data point at 809 F. Changes in the location of that point on Figure 2 can have a profound effect on the slope and intercept.

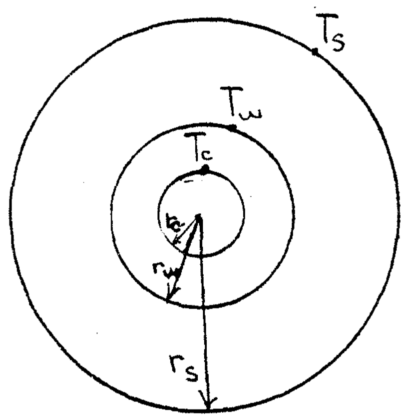
FIGURE 2 : COKING RATE



* COKING RATE IS IN INCHES PER HOUR

** AVERAGE FILM TEMPERATURE IN °R

G. Skin Temperature



The adjacent figure depicts a layer of coke on the inside of a tube wall. Assuming that the heat flux, thermal conductivities, inside and outside radius of the tube, and thickness of the coke is known, the temperature of the outside tube wall (Ts) can be evaluated as follows:

$$T_s = \frac{\left[\frac{1}{k_{COKE}} \ln\left(\frac{r_{WALL}}{r_{COKE}}\right) + \frac{1}{k_{STEEL}} \ln\left(\frac{r_{SKIN}}{r_{WALL}}\right)\right]}{2\pi} \frac{\Delta q}{\Delta z} + T_c \qquad (28)$$

H. Boundary Conditions

Since the velocity profile equations assume fully-developed flow (no end effects), the inlet velocity profile is assumed to be fully-developed at the average inlet velocity specified by the problem.

However, for turbulent flow, the Nikuradse equations contain empirical constants. When the equation is integrated to find the average velocity, it may not always match the value determined by mass balance. Therefore, to ensure mass balance closure, an iterative procedure is used to determine a correction factor (η) which is used to multiply V^* in equations 7 & 8 above. This procedure is discussed further in the chapter on Numerical Analysis.

The initial temperature profile is assumed to be flat at the initial value of bulk temperature specified by the problem.

At the wall, it was assumed that the temperature would be known at two points. The wall profile is then assumed to be linear using the two given values. This boundary condition was chosen instead of constant heat flux because the latter causes serious difficulties when using a numerical solution. A heat flux simply specifies the slope of the temperature profile at the wall:

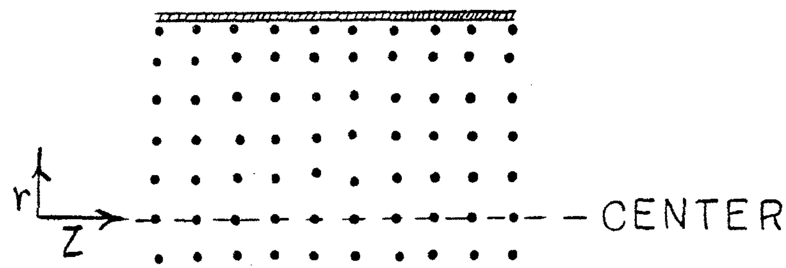
$$q_w = \frac{-k\left(T_w - T_f\right)}{\left(\delta/2\right)}$$

On the right hand side of this equation are two terms that may be independently fixed: Tw and Tf. Furthermore, the turbulent temperature profile can be very steep in the laminar sublayer, and hence Tf is very sensitive to the essentially empirical choice of δ. For these reasons, a stable solution in which we had confidence was not deemed possible with heat flux as a boundary condition.

Similarly, although the wall temperature is specified, it cannot be used directly as a boundary condition. The reason for this is that the temperature profile at the wall is very sensitive to the number of radial points used in the finite difference technique, and it is very easy to develop a profile at the wall that is inconsistent with the overall energy balance. Therefore, to ensure energy balance closure, the film temperature (Tf) is used as the effective boundary condition.

III. Numerical Analysis

In order to solve equation 18 by a finite difference technique, the region of interest must be put into the form of a grid.



Note: The grid convention is that r(1) indicates the radial point next to the wall and r(n) indicates the radial point at the center of the tube.

Grid points in the first column are given the initial conditions, which are a flat temperature profile and a fully-developed velocity profile at the inlet average velocity.

As stated previously, the specified wall temperature is not used directly as a grid point, but rather the film temperature (Tf) is calculated in the middle of the laminar sublayer and used instead as the first row of grid points (closest to the wall). Specifying Tf involves a trial-and-error procedure as described in a subsequent section.

Each gridpoint has a temperature, velocity, and eddy diffusivity associated with it. Each column of gridpoints have a thermal conductivity, heat capacity, density, and viscosity with it, based on the bulk temperature for the previous column of grid points.

A. Laminar Flow

For Reynolds' numbers less than or equal to 2000, the velocity at each grid point is calculated using equation (4) with the average velocity determined by a material balance. Equation (2) is then used to calculate the temperature profile with the same finite difference formulas discussed below, but with $\epsilon_H=0$.

B. Turbulent Flow

Two of the turbulent flow velocity profile equations contain empirical constants (equations 7 & 8). When an average is determined from this profile using equation 17, there is no guarantee that the material balance will be satisfied. In order to ensure material balance closure, V^* in equations (7 & 8) is replaced by ηV^*,

$$\bar{V}_z = \eta V^*(5.0 \ln(Y) - 3.05) \tag{29}$$

$$\bar{V}_z = \eta V^*(2.5 \ln(Y) + 5.5) \tag{30}$$

Where η is determined by trial-and-error using the secant method. In this method, two initial guesses are made for η (usually between 1.1 and 1.4). The turbulent velocity profile is calculated using equations 6, 29, and 30, and the average velocity is calculated using equation 17. The next value of η is then determined as follows:

$$G = \langle V_z \rangle \text{actual} - \langle V_z \rangle \text{calculated} = 0 \tag{31}$$

$$\eta_{i+2} = \eta_{i+1} - \frac{G_{i+1}}{\left(\frac{G_{i+1} - G_i}{\eta_{i+1} - \eta_i}\right)} \tag{32}$$

until $|G| \leqq$ convergence criterion

This procedure is followed for each column of grid points. Resulting values of η are discussed in a later section of this dissertation.

The average velocity is determined by solving equation 17 with the trapezoidal rule. The trapezoidal rule is chosen for two reasons:

1. Either an odd or an even number of radial segments can be chosen.

2. The terms to be evaluated for the numerator and the denominator are plotted in Figure 3. It is clear that the area can be represented well by a linear type of integration method such as the trapezoidal rule.

Expanding equation 18:

$$\frac{1}{r}\left[r\alpha\frac{\partial^2\bar{T}}{\partial r^2}+\alpha\frac{\partial\bar{T}}{\partial r}+r\epsilon_H\frac{\partial^2\bar{T}}{\partial r^2}+\epsilon_H\frac{\partial\bar{T}}{\partial r}+r\frac{\partial\bar{T}}{\partial r}\frac{\partial\epsilon_H}{\partial r}\right]=\bar{V}_Z\frac{\partial\bar{T}}{\partial Z} \tag{33}$$

combining like partial terms:

$$\left(\alpha+\epsilon_H+r\frac{\partial\epsilon_H}{\partial r}\right)\frac{\partial\bar{T}}{\partial r}+r\left(\alpha+\epsilon_H\right)\frac{\partial^2\bar{T}}{\partial r^2}=r\bar{V}_Z\frac{\partial\bar{T}}{\partial Z} \tag{34}$$

The partial derivatives were approximated using the Crank-Nicolson method (30). This method was used rather than (e.g.) a forward difference technique, because the Crank-Nicolson method can converge using much larger axial increments (10^2 times). Since each length increment requires about 1 cpu second to run on a Univac 90/80-4, a 10 foot tube would require 1000 cpu seconds using forward difference as opposed to only 10 cpu seconds using Crank-Nicolson. This saving in computer time would increase for each time segment over which the temperature profiles are calculated along the entire length. The forward difference technique would also display severe temperature instabilities near the wall, with fluid temperatures oscillating and even becoming higher than the wall temperature. The region near the wall is most critical from the standpoint of coking kinetics.

Using Crank-Nicolson, the expressions for the partial derivatives are:

$$\frac{\partial \bar{T}}{\partial Z} = \frac{T_{(n+1,m)} - T_{(n,m)}}{\Delta Z} \tag{35}$$

$$\frac{\partial \bar{T}}{\partial r} = \frac{1}{4\Delta r}\left(T_{(n+1,m+1)} - T_{(n+1,m-1)} + T_{(n,m+1)} - T_{(n,m-1)}\right) \tag{36}$$

$$\frac{\partial^2 T}{\partial r^2} = \frac{1}{2(\Delta r)^2}\left(T_{(n+1,m+1)} - 2\,T_{(n+1,m)} + T_{(n+1,m-1)} + T_{(n,m+1)} - 2\,T_{(n,m)} + T_{(n,m-1)}\right) \tag{37}$$

where the following convention for subscripts was used:

n is for the z coordinate (axial direction); n=1 is the point closest to the tube inlet

m is for the r coordinate (radial direction); m=1 is the point closest to the wall. m=M is the point at the center.

Let

$$\beta_m = \left(\frac{\Delta Z}{4\Delta r}\right)\left(\frac{\alpha_n + \epsilon_{Hm}}{V_{z_{n,m}} r_m}\right) \tag{38}$$

$$\gamma_m = \frac{\Delta Z}{2(\Delta r)^2}\left(\frac{\alpha_n + \epsilon_{Hm}}{V_{z_{n,m}}}\right) \tag{39}$$

$$\xi_m = \frac{\Delta Z}{4\Delta r\, V_{z_{n,m}}}\left(\frac{\partial \epsilon_H}{\partial r}\right)_m \tag{40}$$

where

$$\left(\frac{\partial \epsilon_H}{\partial r}\right)_m = \frac{\epsilon_{H(n,m+1)} - \epsilon_{H(n,m-1)}}{2\Delta r} \tag{41}$$

and

$$\epsilon_{H(n,m)} = \ell^2_{(n,m)} \left[\frac{\bar{V}_{Z(n,m+1)} - \bar{V}_{Z(n,m)}}{\Delta r} \right] \qquad (42)$$

(Note: the eddy diffusivity along the centerline approaches zero, and so was set equal to the value at the next radial grid point.)

$$\ell_{(n,m)} = \left(R - r_{(m)}\right) 0.36 \left[1 - \frac{26}{Y_{(n,m)}} \right] \qquad (43)$$

$$Y_{(n,m)} = \left(R - r_{(m)}\right) V^*_{(n)} \frac{\rho_{(n)}}{\mu_{(n)}} \qquad (44)$$

$$V^*_{(n)} = \langle V_Z \rangle \sqrt{\frac{f_{(n)}}{2}} \qquad (45)$$

Substituting into equation 34:

$$\begin{aligned} &\beta_m\left(T_{(n+1,m+1)} - T_{(n+1,m-1)} + T_{(n,m+1)} - T_{(n,m-1)}\right) + \\ &\gamma_m\left(T_{(n+1,m+1)} - 2T_{(n+1,m)} + T_{(n+1,m-1)} + T_{(n,m+1)} - 2T_{(n,m)} + T_{(n,m-1)}\right) + \\ &\xi_m\left(T_{(n+1,m+1)} - T_{(n+1,m-1)} + T_{(n,m+1)} - T_{(n,m-1)}\right) - T_{(n+1,m)} + T_{(n,m)} = 0 \end{aligned} \qquad (46)$$

Combining like terms:

$$\begin{aligned} &T_{(n+1,m+1)}\left(\beta_m + \gamma_m + \xi_m\right) + T_{(n+1,m)}\left(-2\gamma_m - 1\right) + T_{(n+1,m-1)}\left(-\beta_m + \gamma_m - \xi_m\right) \\ &= -T_{(n,m+1)}\left(\beta_m + \gamma_m + \xi_m\right) - T_{(n,m)}\left(-2\gamma_m + 1\right) - T_{(n,m-1)}\left(-\beta_m + \gamma_m - \xi_m\right) \end{aligned} \qquad (47)$$

Equation 47 is valid at all points except those along the centerline, where 1/r is undefined. Using L'Hôpitals' rule at the centerline:

$$\lim_{r\to 0}\left(\frac{1}{r}\frac{\partial T}{\partial r}\right)=\left(\frac{\partial^2 \bar{T}}{\partial r^2}\right)\Bigg|_{r=0} \tag{48}$$

$$\frac{\alpha+\epsilon_H}{r}\frac{\partial \bar{T}}{\partial r}=(\alpha+\epsilon_H)\left(\frac{\partial^2 \bar{T}}{\partial r^2}\right)\Bigg|_{r=0} \tag{49}$$

Substituting into equation (18):

$$(\alpha+\epsilon_H)\left(2\frac{\partial^2 \bar{T}}{\partial r^2}\right)+\frac{\partial \bar{T}}{\partial r}\frac{\partial \epsilon_H}{\partial r}=\bar{V}_z\frac{\partial \bar{T}}{\partial Z} \tag{50}$$

Defining

$$\gamma_m' = \Delta Z\left(\frac{\alpha_n+\epsilon_{H_n}}{(\Delta r)^2 V_{z_{n,m}}}\right) \tag{51}$$

Equation 50 may be rewritten in terms of Crank-Nicolson finite difference expressions:

$$\begin{aligned}&\gamma_m'\left(T_{(n+1,m+1)}-2T_{(n+1,m)}+T_{(n+1,m-1)}+T_{(n,m+1)}-2T_{(n,m)}+T_{(n,m-1)}\right)\\&+\xi_m\left(T_{(n+1,m+1)}-T_{(n+1,m-1)}+T_{(n,m+1)}-T_{(n,m-1)}\right)-T_{(n+1,m)}+T_{(n,m)}=0\end{aligned} \tag{52}$$

Combining like terms:

$$\begin{aligned}&T_{(n+1,m+1)}(\gamma_m'+\xi_m)+T_{(n+1,m)}(-2\gamma_m'-1)+T_{(n+1,m-1)}(\gamma_m'-\xi_m)\\&=-T_{(n,m+1)}(\gamma_m'+\xi_m)-T_{(n,m)}(-2\gamma_m'+1)-T_{(n,m-1)}(\gamma_m'-\xi_m)\end{aligned} \tag{53}$$

By symmetry, ξ_m, at the centerline is equal to zero because $\dfrac{\partial \epsilon_H}{\partial r} = 0$; therefore equation 53 can be written as:

$$
\begin{aligned}
&T_{(n+1,m+1)}(\gamma_m') + T_{(n+1,m)}(-2\gamma_m' - 1) + T_{(n+1,m-1)}(\gamma_m') \\
&= -T_{(n,m+1)}(\gamma_m') - T_{(n,m)}(-2\gamma_m' + 1) - T_{(n,m-1)}(\gamma_m')
\end{aligned} \tag{54}
$$

also by symmetry:

$$T_{(n+1,m-1)} = T_{(n+1,m+1)} \tag{55}$$

$$T_{(n,m-1)} = T_{(n,m+1)} \tag{56}$$

placing equations 55 and 56 into 54:

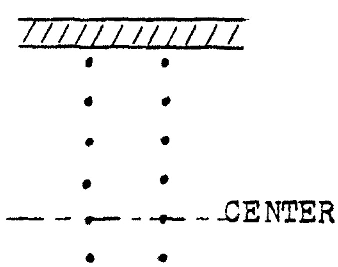
$$T_{(n+1,m)}(-2\gamma_m' - 1) + T_{(n+1,m-1)}(2\gamma_m') = -T_{(n,m)}(-2\gamma_m' + 1) - T_{(n,m-1)}(2\gamma_m') \tag{57}$$

When solving for the first unknown temperature next to the wall equation 47 can be simplified since the temperature next to the wall is a boundary condition.

$$
\begin{aligned}
&T_{(n+1,m)}(-2\gamma_m - 1) + T_{(n+1,m+1)}(\beta_m + \gamma_m + \xi_m) \\
&= -T_{(2,1)}(-\beta_m + \gamma_m - \xi_m) - T_{(1,1)}(-\beta_m + \gamma_m - \xi_m) \\
&\quad - T_{(n,m+1)}(\beta_m + \gamma_m + \xi_m) - T_{(n,m)}(-2\gamma_m + 1)
\end{aligned} \tag{58}
$$

Solving for the temperature profile using a tridiagonal matrix:

Consider 5 radial values:



For clarity let

$$A_m = \beta_m + \gamma_m + \xi_m$$

$$C_m = -2\gamma_m - 1$$

$$D_m = -\beta_m + \gamma_m - \xi_m$$

$$E_m = -T_{(n,m+1)} A_m - T_{(n,m)}(-2\gamma_m + 1) - T_{(n,m-1)} D_m$$

making these substitutions into equation 47 we obtain

$$T_{(n+1,m+1)} A_m + T_{(n+1,m)} C_m + T_{(n+1,m-1)} D_m = E_m \qquad (58)$$

Also, let

$$F_m = -2\gamma_m' - 1$$

$$G_m = 2\gamma_m'$$

$$H_m = -(-2\gamma_m' + 1) T_{(n,m)} - T_{(n,m-1)} (2\gamma_m')$$

Equation 57 with these substitutions becomes:

$$T_{(n+1,m)} F_m + T_{(n+1,m-1)} G_m = H_m \qquad (59)$$

Finally, let $I_m = -T_{(2,1)} D_m - T_{(1,1)} D_m - T_{(n,m+1)} A_m$

$$- T_{(n,m)} (-2\gamma_m + 1)$$

and with this substitution equation 58 is now:

$$T_{(n+1,m)} C_m + T_{(n+1,m+1)} A_m = I_m \qquad (60)$$

(Reminder: "n" refers to the z coordinate, and "m" the r coordinate)

The tridiagonal matrix is set up for n=1 as follows (Remember at the first radial grid point the film temperature is known):

(m)					
2	$(C2)T_{(2,2)}$	$(A2)T_{(2,3)}$	0	0	= I2 EQ.60
3	$(D3)T_{(2,2)}$	$(C3)T_{(2,3)}$	$(A3)T_{(2,4)}$	0	= E3 EQ.58
4	0	$(D4)T_{(2,3)}$	$(C4)T_{(2,4)}$	$(A4)T_{(2,5)}$	= E4 EQ.58
5	0	0	(G5)T(2,4)	(F5)T(2,5)	= H5 EQ.59

The N-1 equations and N-1 unknowns are solved by using a standard tridiagonal matrix algorithm (31).

C. Transition Flow

In the Reynolds' number range from 2000 to 4000, the velocity profile is determined using the equations for laminar and turbulent flow, as described above, and equation 23.

D. Bulk Temperature

In calculating the bulk temperature, equation 24 is solved using the trapezoidal rule. This appears to be an effective method as indicated by Figures 3 and 4.

Equation 24 with the finite difference approximations to the trapezoidal rule is:

$$T_{\substack{bulk \\ @ z=n}} = \frac{\sum_{j=1}^{M-1} V_z(n,j)\, T(n,j)\, r(j)}{\sum_{j=1}^{M-1} V_z(n,j)\, r(j)} \qquad (61)$$

FIGURE 3 : NUMERATOR FOR AVERAGE VELOCITY AND DENOMINATOR FOR BULK TEMPERATURE

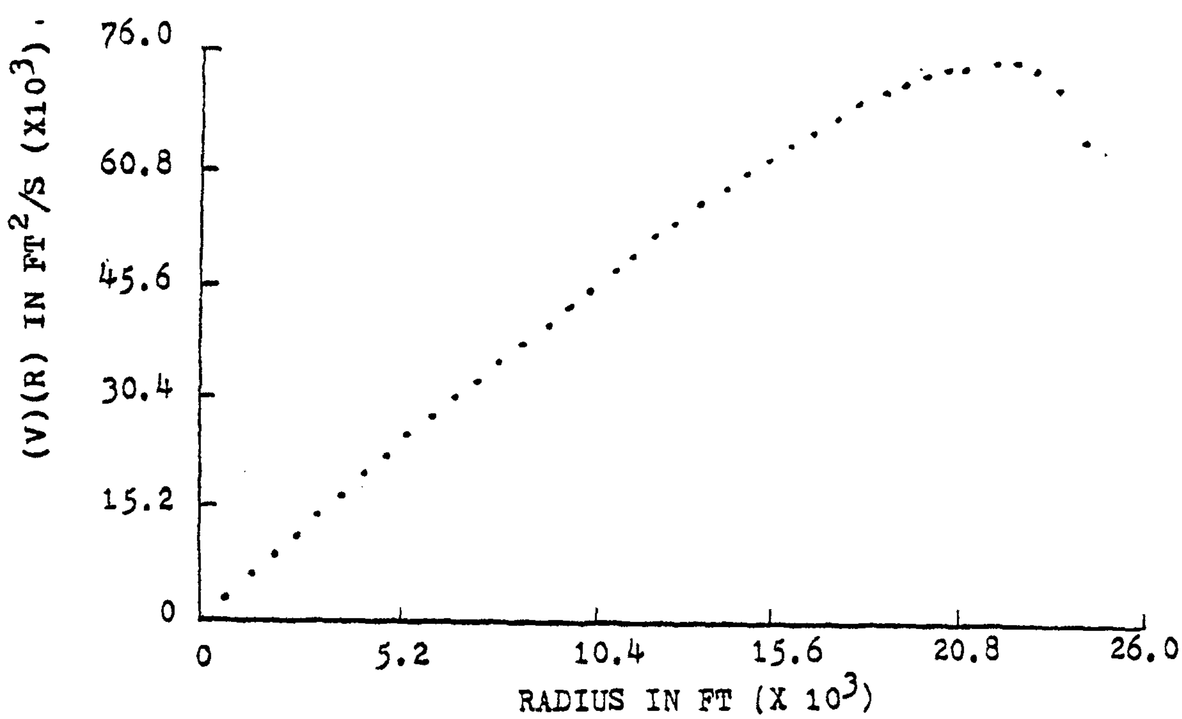
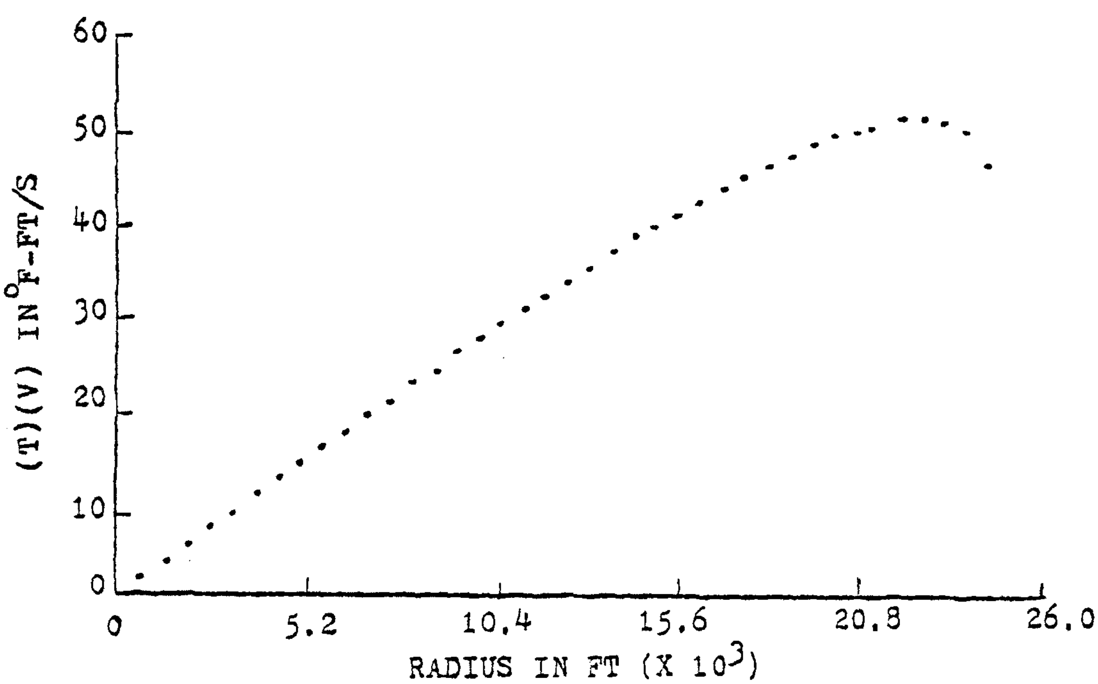


FIGURE 4 : NUMERATOR FOR BULK TEMPERATURE



Film Temperature

The initial value of the film temperature is taken to be the same as the wall temperature. After obtaining the temperature profile, the bulk temperature is determined, and equation 26 is used to calculate Δq. Then, a new film temperature is calculated using equation 25. The procedure is repeated until the film temperature converges.

F. Kinetic Rate Constant

Once the profile for the entire length of the tube has been determined, the coke is layered using equation 27. The user supplies the value for the time increment during which the coke is deposited. The amount of coke (in inches) then reduces the inside tube radius for the next time increment. The calculations are then repeated for the crude oil temperature profile along the entire tube length, more coke is deposited, and so on.

G. Skin Temperature

The outside skin temperature of the tube is determined using equation 28. The skin temperature is calculated after the film temperature (and therefore the temperature profile) has converged.

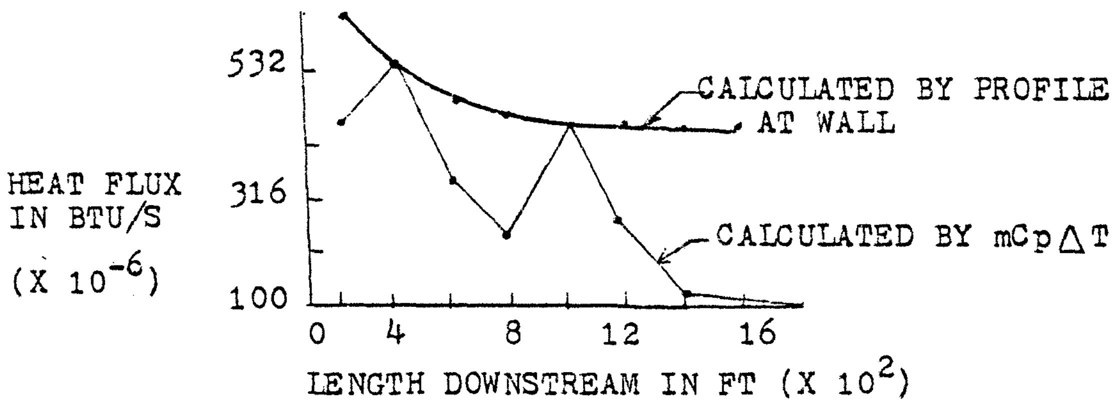
H. Boundary Conditions and Stability

The initial boundary conditions (at z=0) is a flat temperature profile equal to the average inlet bulk temperature, and a fully-developed velocity profile based on the average inlet velocity. However, the second boundary condition on temperature, at the wall, presented special problems.

All finite difference methods have the potential for instability. When the wall temperature is used as a boundary condition, the method will not converge for a typical case (such as series D4) unless there are 2000 equal radial segments. Naturally 2000 radial segments is ridiculous, assuming that no round-off error is encountered, 900 cpu seconds would be required for a 9 foot tube, as opposed to only 9 cpu seconds using 30 radial segments (with 1 ft axial segments, and using the Crank-Nicolson method). In an attempt to correct this situation, the Crank-Nicolson equations were re-derived so that only the first few radial segments closest to the wall were small while the segments in the bulk liquid were relatively large. This change, however, resulted in temperature oscillations, and in some cases fluid temperatures higher than the wall temperature, unless the size of the axial increment was reduced to 0.01 ft. This was the same problem encountered using the forward difference technique. In addition a heat balance done on each axial segment revealed that the heat balance was not closing. The pattern followed is shown in Figure 32.

In an effort to solve both the problems of stability and heat balance closure, the program was changed to utilize the film temperature rather than the wall tempera-

FIGURE 32: BEFORE USING FILM TEMPERATURE

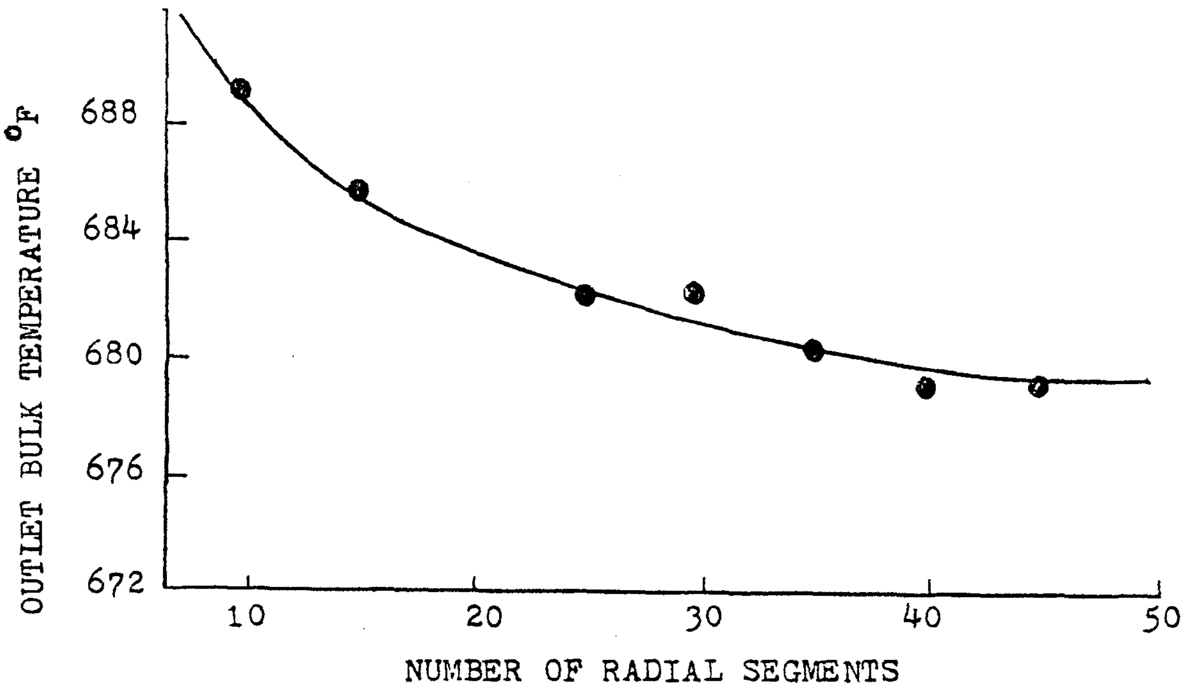


ture as the boundary condition. The initial guess for the film temperature is the wall temperature. The bulk temperature is then determined from the temperature profile, and a heat balance is used to determine the film temperature as described in equations 25 and 26. This procedure is iterated by successive substitution until the film temperature converges. If instead of a linear temperature profile assumed for the laminar sublayer, a parabolic profile is used, the calculated film temperature is the same but it requires 10 more iterations to converge. Hence, a linear profile is used in the program.

Therefore, the temperature next to the wall, which causes all the stability problems, is determined in a way which causes virtually no stability problems. For 40 radial segments, an axial segment of 0.5 feet is sufficient for stability and accuracy.

The proper number of radial segments to use was found by plotting the final bulk temperature (for series D4) using a variety of radial segments. Figure 33 indicates that 40 is the proper number of radial segments for accuracy and speed. The size of the axial segment was not found to affect the bulk temperature appreciably. However, decreasing the axial segment in half required twice as much computer time to calculate the temperature profile. For a nine foot tube with series D4, 40 radial segments, and an axial segment of 0.5 feet, the program requires about 30 cpu seconds to calculate the temperature profile for the entire length.

FIGURE 33: OPTIMAL NUMBER OF RADIAL SEGMENTS FOR SERIES D4



Since many calculations are required in this program, the entire program was re-written with double precision. The results were essentially the same (the bulk temperature differed slightly in the fourth decimal place). Since double precision requires much more memory and more time to run, the program used is the single precision version.

The program uses tolerance values for the film temperature and for the calculation of η. The tolerances were chosen to be the smallest that can be used without causing oscillation. If tolerances smaller than the present values are used for the series run in this dissertation, oscillation occurs, and no results are obtained.

IV. Description of Computer Program

A. General Description

After the crude oil parameters and tube dimensions are read, the velocity profile, temperature profile, and other important quantities (NRe, Bulk Temperature, etc.) are calculated starting from the first length segment and continuing downstream until reaching the end of the tube. At each length segment the physical properties of the crude oil are updated. Time is not incremented at each length segment. Time is incremented when all the calculations for an entire length have been completed.

Once an entire length has been completed, a uniform coke layer is added to the inside of the tube. The amount of coke is determined based upon the film temperature and the time increment. The velocity and temperature distributions are then calculated based upon the new value of the flow area.

This program requires the temperature of the inside of the tube wall at each length increment, constant heat flux is not necessary. The program assumes that the temperature and velocity profiles initially entering the tube are flat.

In order to save memory requirements the velocity and temperature profile arrays contain only 2 columns. Column 1 contains the past length segment values, column 2 contains the present values. Once all the calculations for a length segment are complete the arrays are reset with subroutine RESET (i.e. the present value in column 2 becomes the past value and is placed in column 1).

B. Program Specifics

Figure 5 shows the hierarchy diagram for the program. The flow chart for the MAIN program is shown in Figure 6. The MAIN program is responsible for calling the second level subroutines and incrementing the length and time. The main routine also insures that the temperature profile follows a heat balance by calling subroutine TADJ which adjusts the temperature next to the wall. This will be discussed further below.

MAIN starts by calling subroutine INIT (Figure 7), which initializes flags and important variables. Main then calls subroutine READER (Figure 8), which reads in the API gravity and mid-boiling temperature of the crude, the mass flow rate, inlet temperature, and wall temperature. In addition, it reads the specified number of radial and axial segments, the time increment, and variables used to control the printing of results. Once these variables are read in with READER, INIT sets the initial temperature array to the bulk temperature of the crude oil entering. Finally INIT calls PRN1 (Figure 9), which prints some of the important data read in subroutine READER.

Once INIT is complete and control is back to MAIN, a loop which counts the number of axial segments is begun. The first step of this loop is to call PHYP (Figure 10), which calculates the physical properties (density, thermal conductivity, heat capacity etc.) of the crude oil based upon the bulk temperature of the previous length segment. The viscosity is calculated by calling function VISC (Figure 11). Once the physical properties are determined, routine PHYP determines the average velocity by performing a mass balance using the mass flow rate and the cross-sectional area of flow. The flow area is not necessarily the cross-sectional area of the tube, because as the coke layer builds up the flow area is restricted. Once the average velocity is calculated, the Reynolds number and laminar sublayer thickness are calculated. Routine PHYP also determines the thickness of the laminar sublayer using the equations given previously. Once the thickness of the laminar sublayer is determined, the size of each radial segment is determined by subtracting one half of the laminar sublayer from the radius of flow, and then dividing by the number of specified radial segments.

The temperature of the wall for a particular length segment is calculated using WALLT (Figure 12), which takes two known wall temperatures specified in the data and assumes a linear profile. This profile is then extrapolated to cover the entire tube length.

RENVL (Figure 13) is a routine which decides which flow regime is applicable and calls the appropriate velocity subroutine. Laminar flow is considered to have a Reynolds number less than 2000, turbulent flow greater than 4000, and the transition region is between 2000 and 4000. If the Reynolds number is under 2000, RENVL calls subroutine LAMAR (Figure 14), which calculates the velocity profile using equation 4. If the Reynolds number is greater than 4000, RENVL calls TURB (Figure 15), which uses two guesses (1.0 and 1.4) to the velocity correction factor, η , and then calls VPP (Figure 20), which determines the velocity profile using equations 6, 29, and 30; TVAVG (Figure 17), which determines the average velocity using the trapezoidal rule (Subroutine TRAP Figure 18); and SECANT (Figure 19), which performs the trial-and-error to obtain the appropriate value of η in order to close the material balance on $\langle Vz \rangle$. SECANT determines the next guess for the velocity correction factor, η , in order to get the average velocities to match. Once they match within a specified tolerance, control is given back to the main routine.

If the Reynolds number is between 2000 and 4000, subroutine TRANS is called (Figure 21), which calculates both the laminar profile (by calling LAMAR) and the turbulent profile (by calling TURB). The transition velocity profile is then based on a linear combination of both profiles, using a weighting factor which is proportional to the Reynolds number (see equation 23).

Once the velocity profile is determined control is restored to MAIN. The next step is to call TEMP (Figure 22), which calls EDDY and then TCRANK.

EDDY (Figure 23) determines the values of the eddy diffusivity for each radial point. If the flag, KTFLG, is equal to zero then the flow is laminar and the eddy diffusivity for each radial segment is zero. For turbulent flow, the eddy diffusivity is calculated as described in the numerical section.

Once EDDY has been called, routine TEMP calls TCRANK (Figure 24), which sets up the terms for the tridiagonal matrix described in the numerical section. Once the appropriate terms are placed in the tridiagonal matrix, the matrix is solved with TRIDAG (Figure 25).

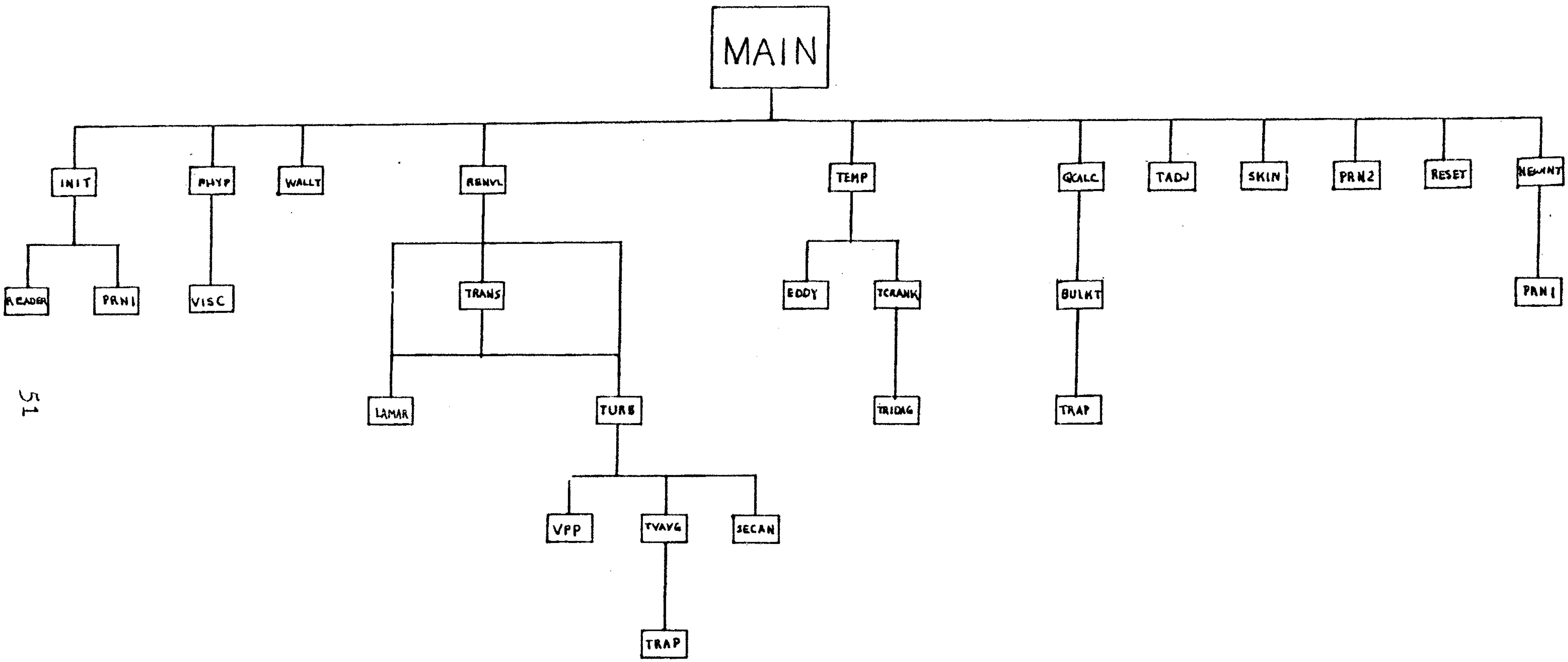
Once the temperature profile is determined, control is passed back to the main routine where QCALC is called (Figure 26), which determines the heat flux for the axial segment the program. QCALC calls BULKT (Figure 27), a subroutine to determine the bulk temperature using the trapezoidal integration method. Once the bulk temperature for the present axial segment is known, QCALC performs a heat balance to determine what the heat flux should be. The first guess for the temperature of the laminar sublayer is the same as the wall temperature, and a new value is generated by TADJ, (Figure 28), which uses the heat flux calculated in QCALC and a linear profile to determine the film temperature. It then iterates back to TEMP until convergence is reached on Tf. Once the temperature converges, SKIN is called (Figure 29) which calculates the temperature of the outside of the tube wall.

The program prints the results with routine PRN2 (Figure 16). Array IPRN and variable NPRN are used to limit the computer printout. The results for each axial segment for the entire tube length will be printed, but only at the time increments specified. For example: If the total time of the test is 200 hours, and you want the coke to be layered at 100 and at 200 hours. There are three time segments (initial, 100 and 200 hours), but say only the value for the initial time and at 200 hours are desired. NPRN has the number of time increments to be printed, in this case NPRN is two. Array IPRN will have 2 values which correspond to the desired time increment. In this case IPRN(1) would equal zero (for the initial time segment) and IPRN(2) would equal two (for the value at 200 hours).

Once a length segment is completed, the V and T arrays are changed with RESET (Figure 30) so that the second column becomes the first. Once an entire length is completed the time is incremented by an amount, DTIME. If the total time is reached the program ends, otherwise subroutine NEWINT (Figure 31) is called which calculates the average film temperature, and then the coke thickness using the specified kinetic rate constant. NEWINT also determines the new flow area, and initializes variables for the next time segment.

In the next time segment, the temperature at the coke-crude oil interface is considered to be the same as the initial temperature at the tube wall-crude oil interface.

FIGURE 5: HIERARCHY DIAGRAM FOR PROGRAM



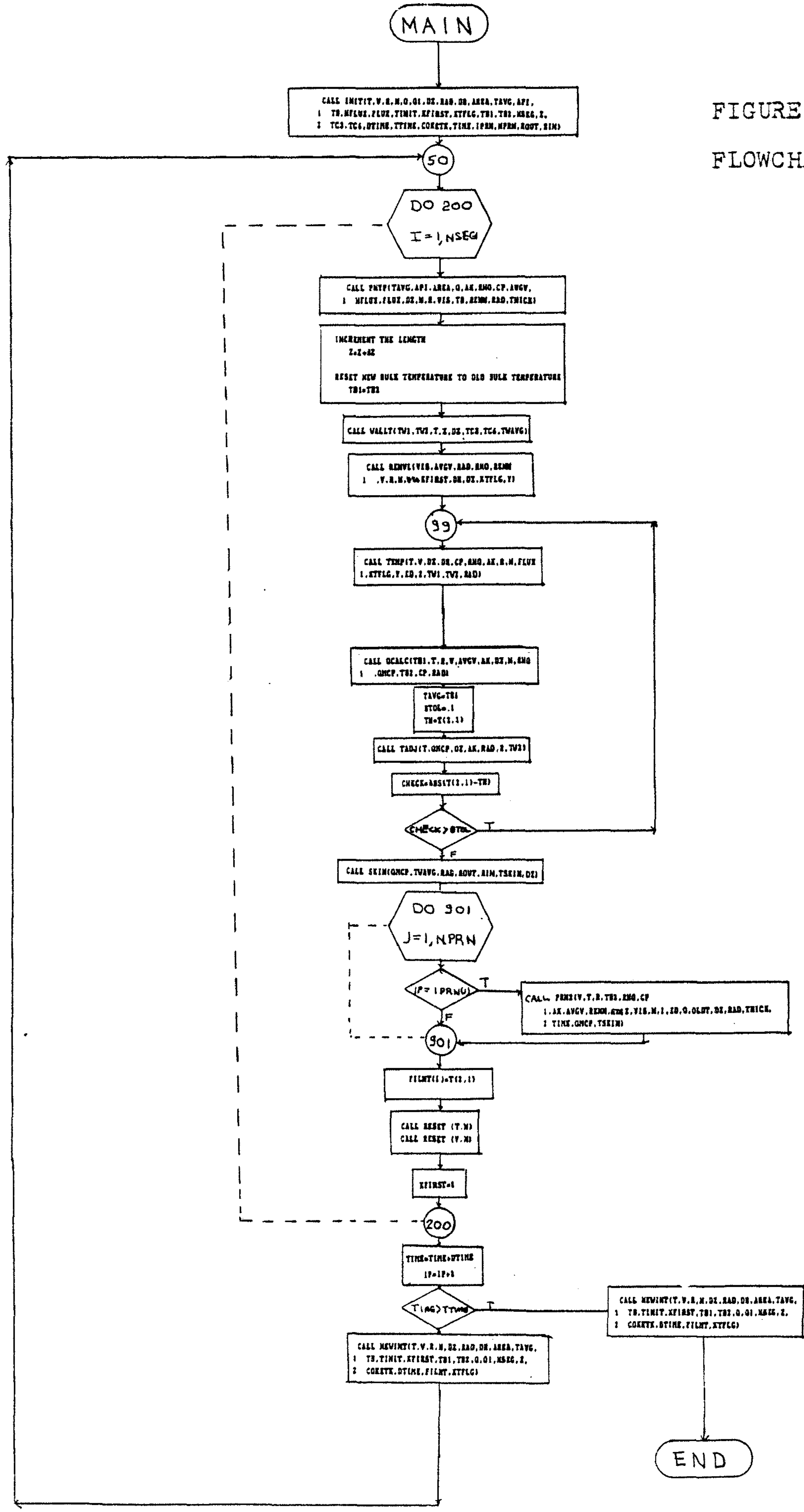


FIGURE 6

FLOWCHART OF MAIN

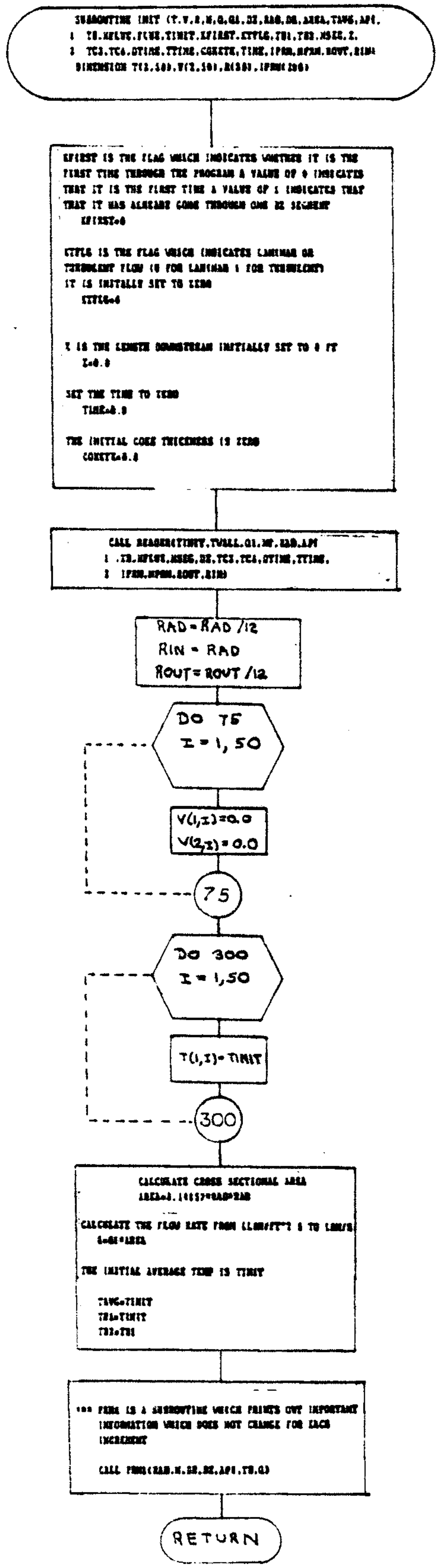


FIGURE 7:

FLOWCHART OF

SUBROUTINE INIT

FIGURE 8: FLOWCHART OF SUBROUTINE READER

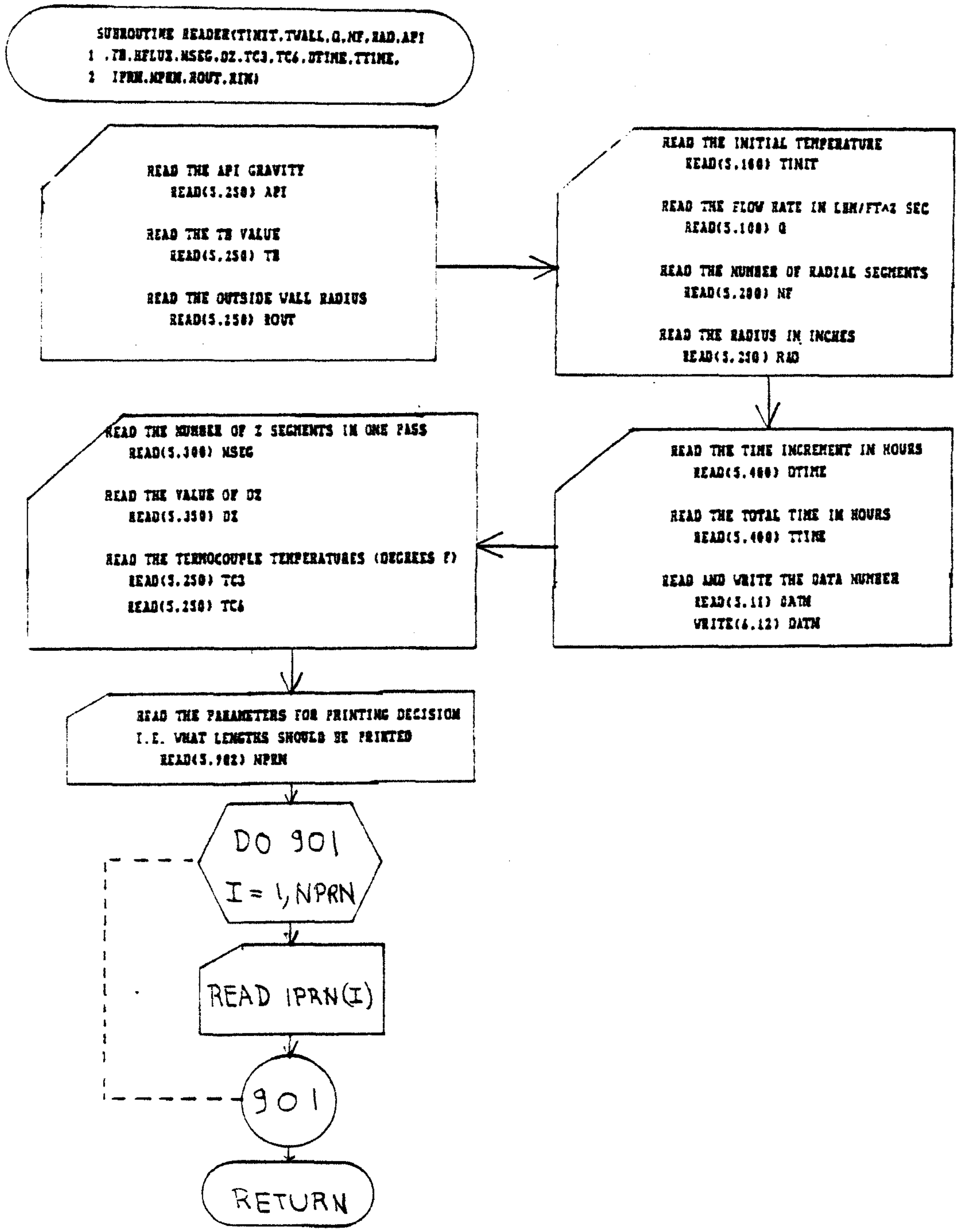


FIGURE 9: FLOWCHART OF SUBROUTINE PRN1

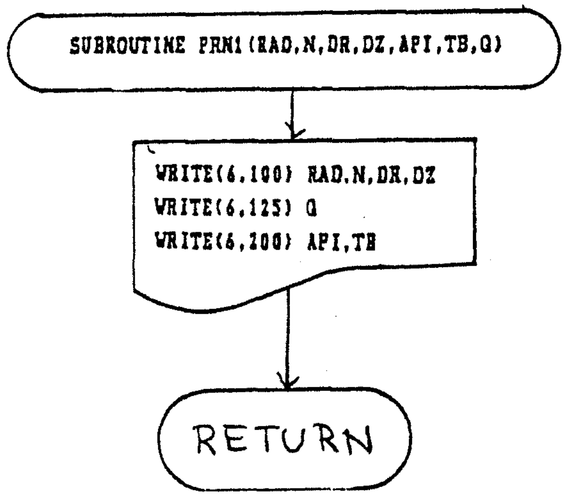


FIGURE 10: FLOWCHART OF SUBROUTINE PHYP

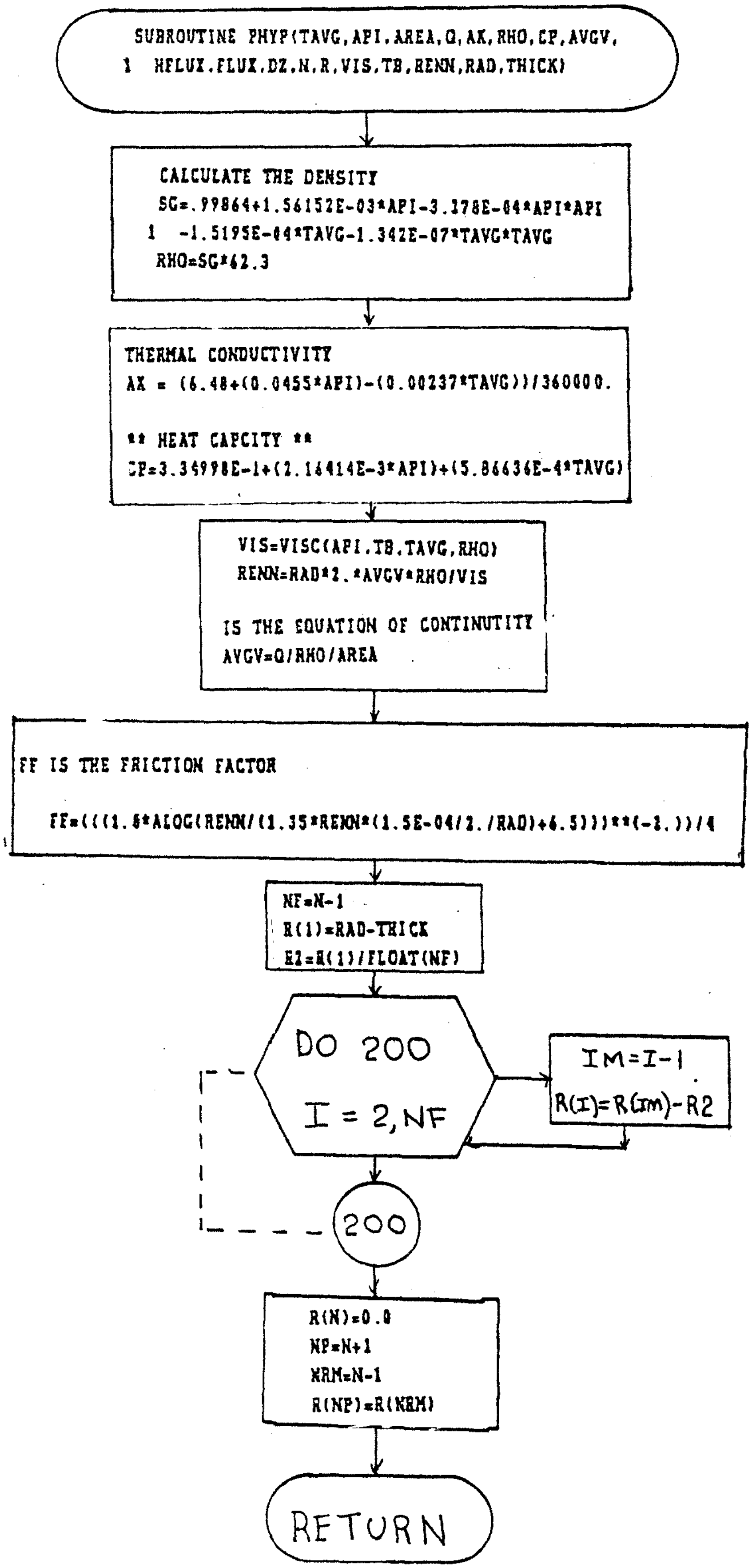


FIGURE 11: FLOWCHART OF FUNCTION VISC

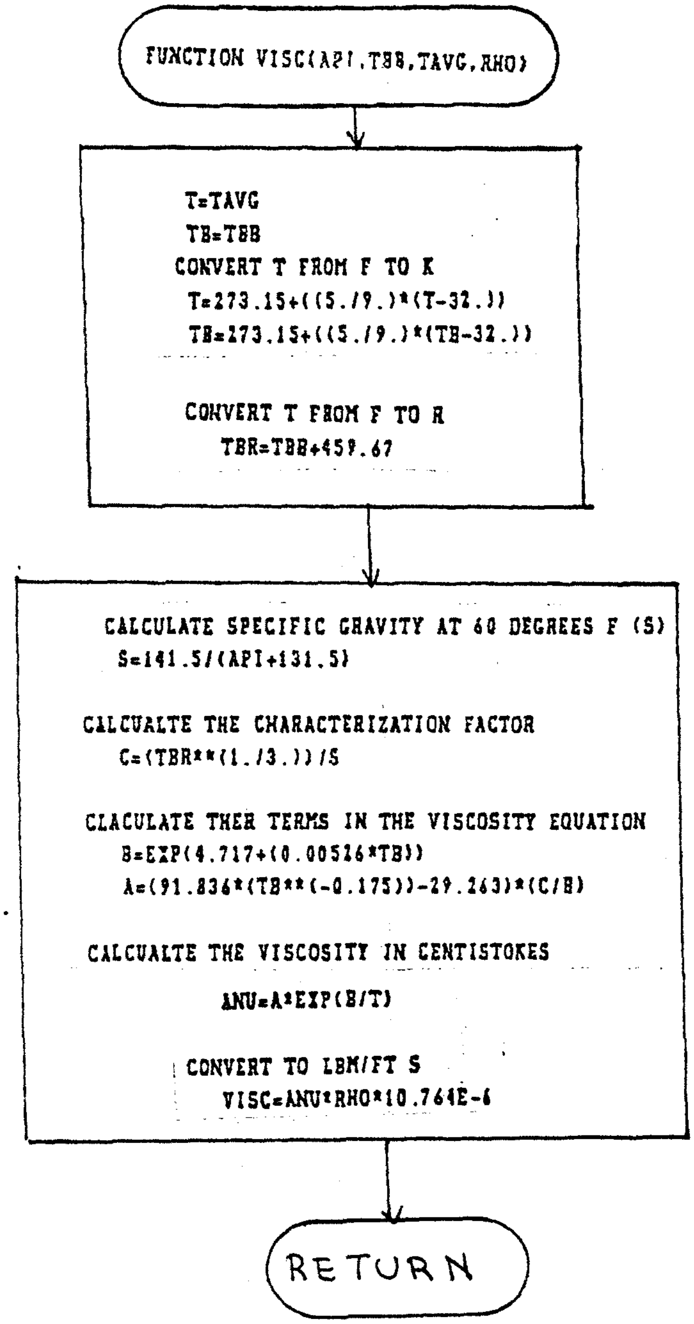


FIGURE 1 FLOWCHART OF SUBROUTINE WALLT

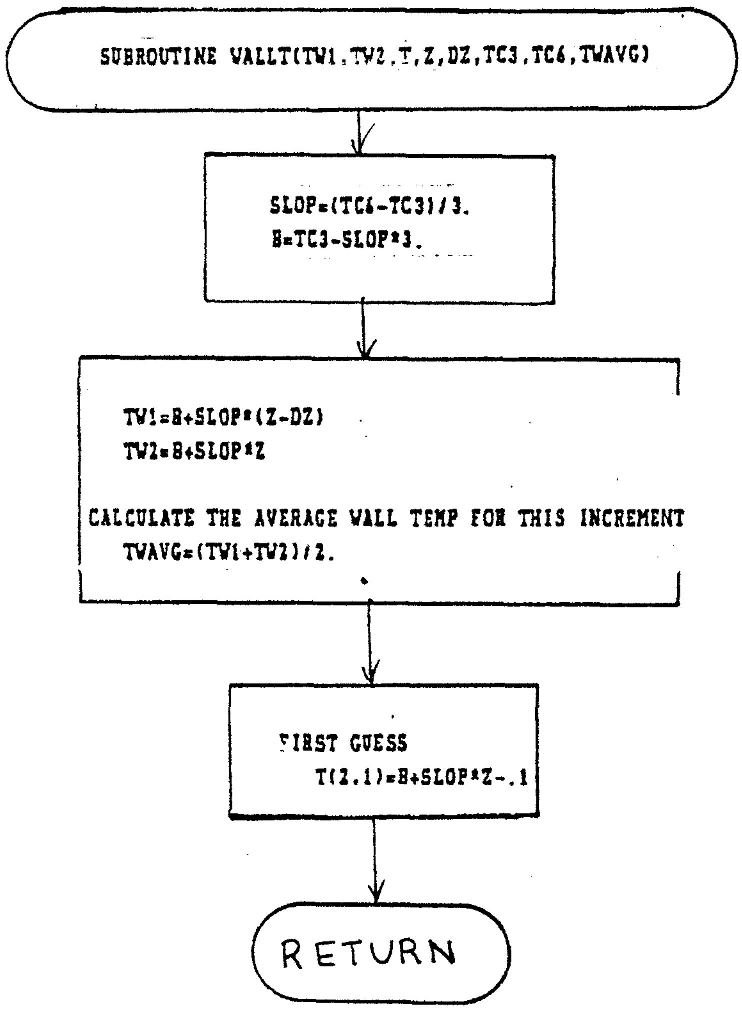


FIGURE 13: FLOWCHART OF SUBROUTINE RENVL

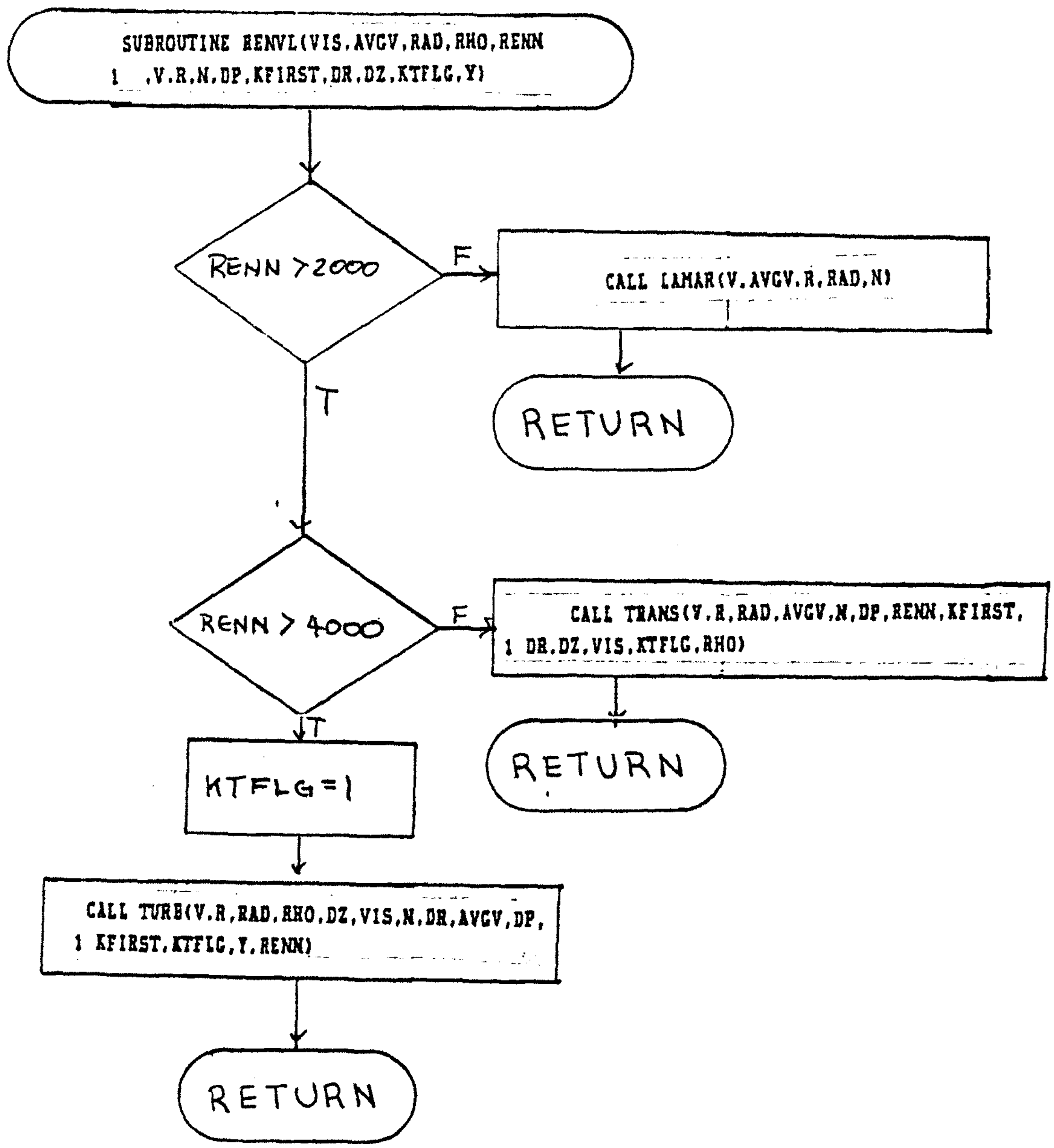


FIGURE 14: FLOWCHART OF SUBROUTINE LAMAR

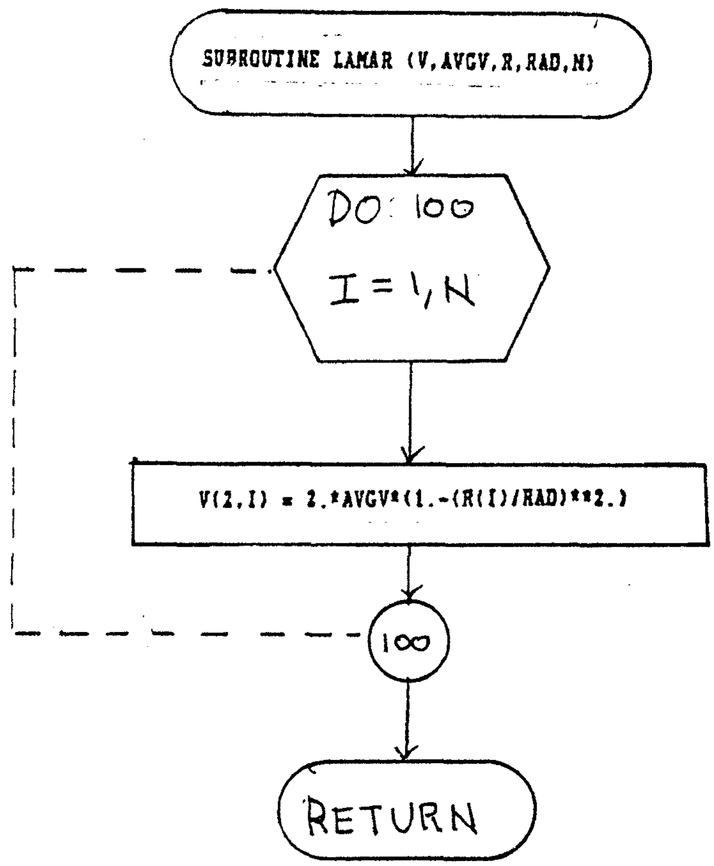


FIGURE 15: FLOWCHART OF SUBROUTINE TURB

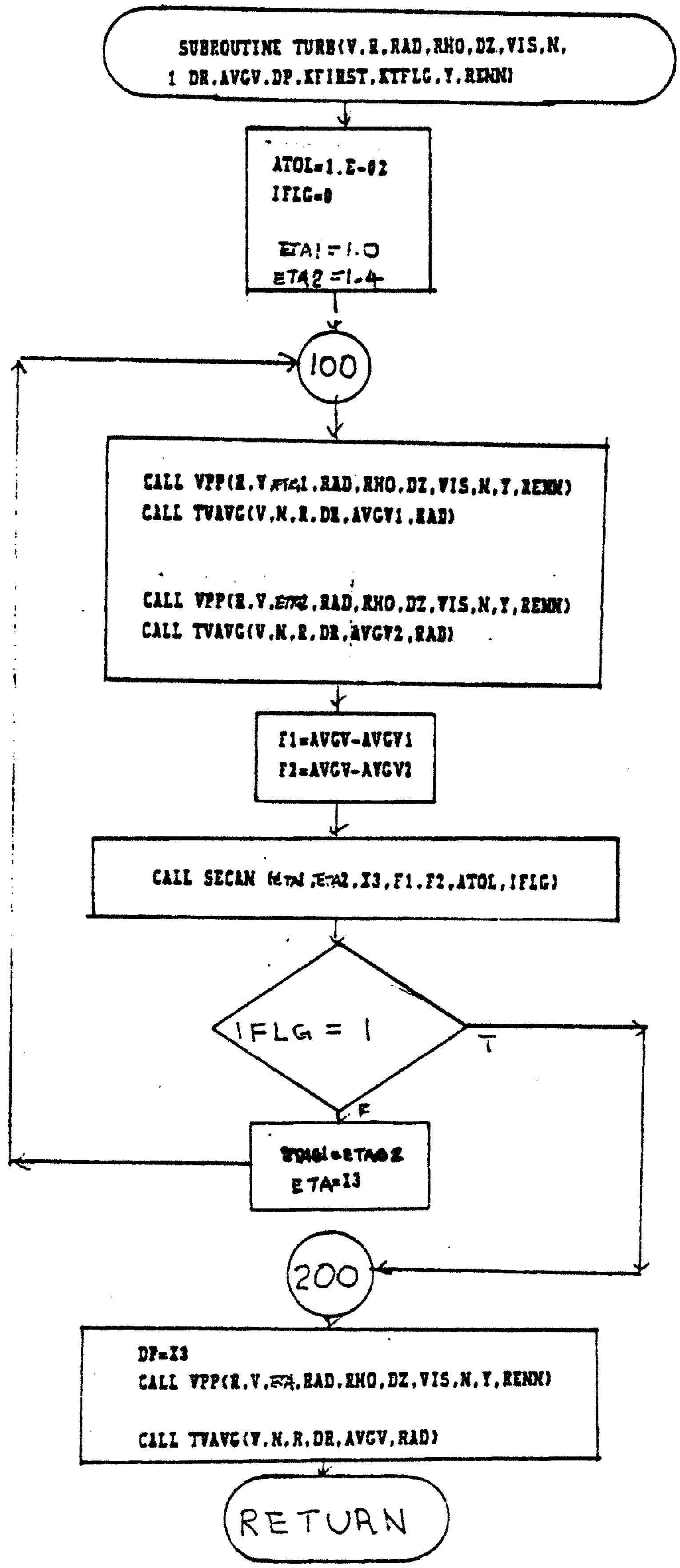


FIGURE 16: FLOWCHART OF SUBROUTINE PRN2

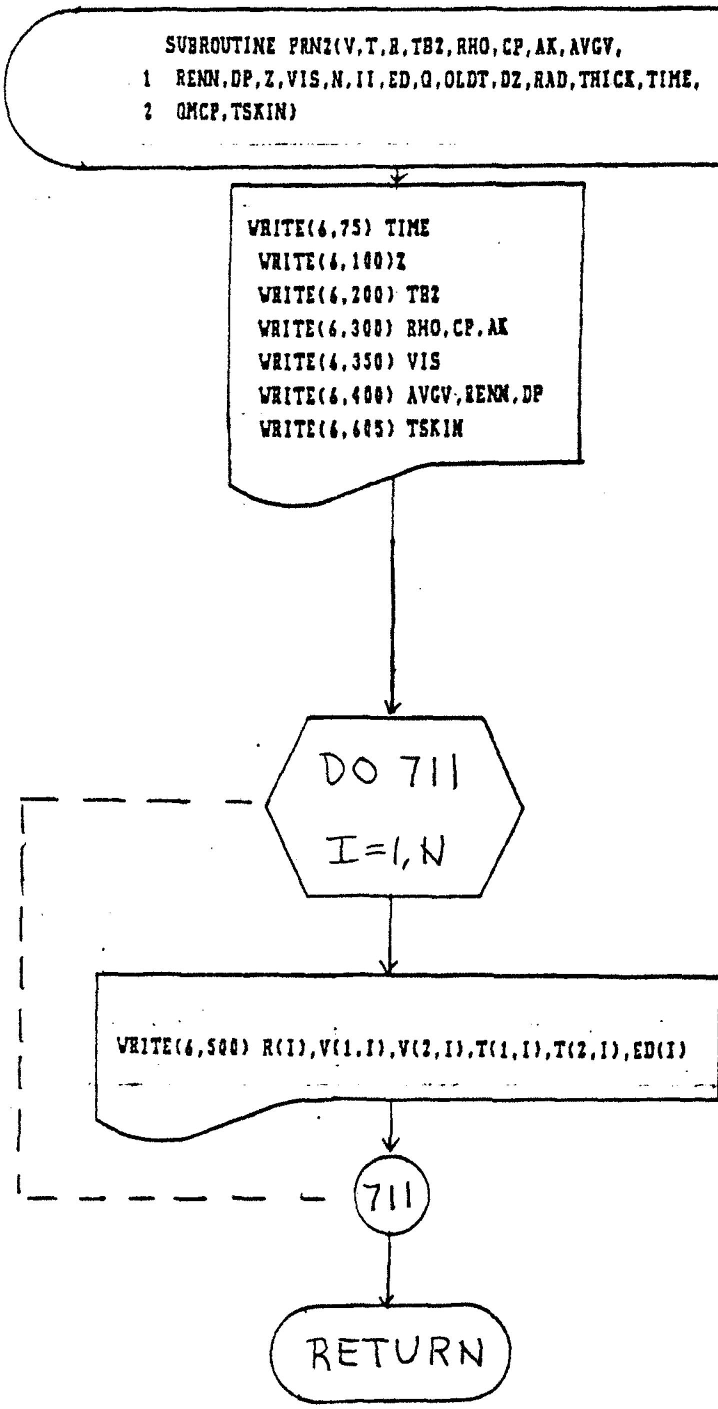


FIGURE 17: FLOWCHART OF SUBROUTINE TVAVG

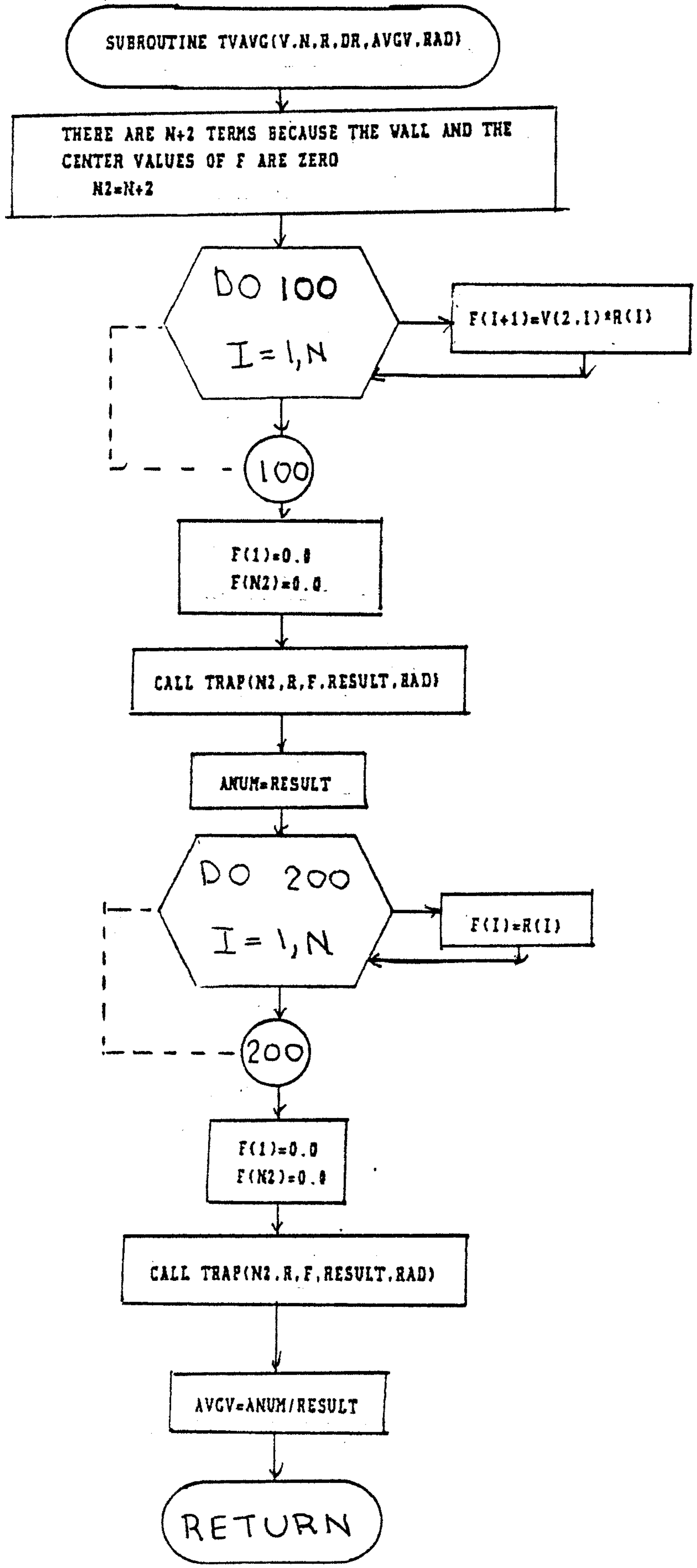


FIGURE 18: FLOWCHART OF SUBROUTINE TRAP

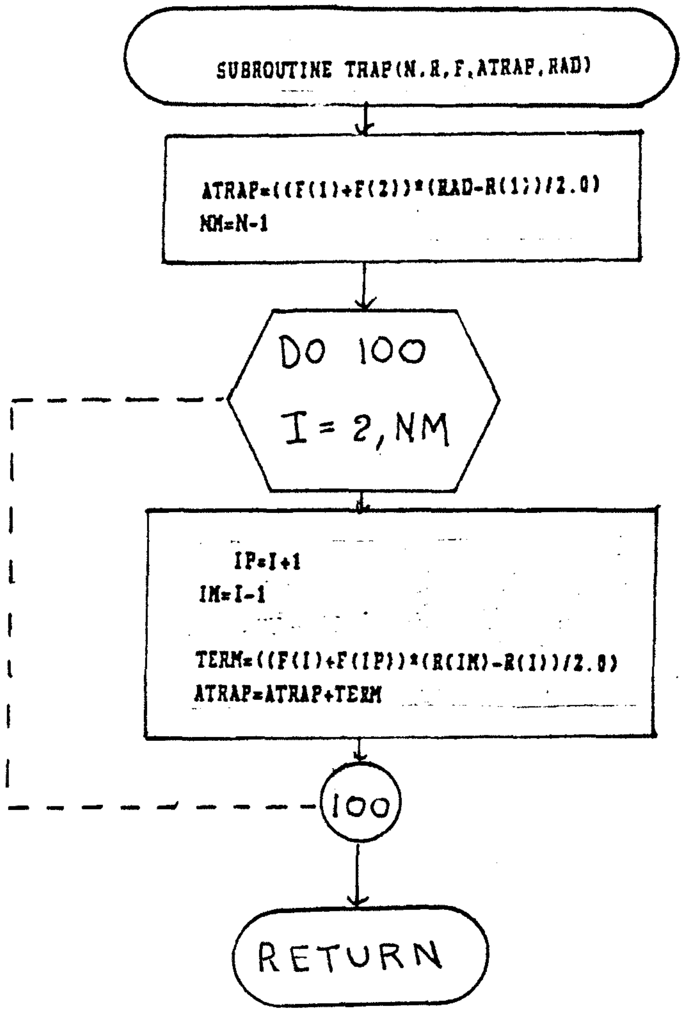


FIGURE 19: FLOWCHART OF SUBROUTINE SECAN

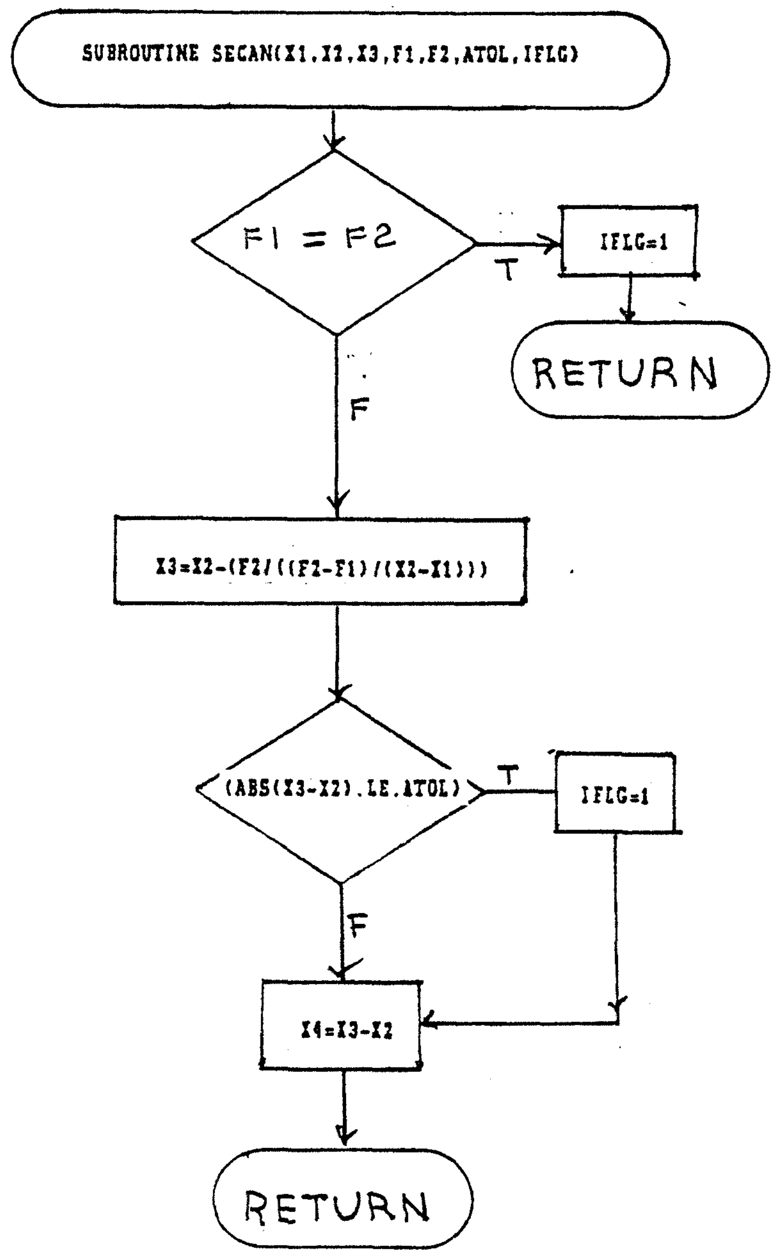


FIGURE 20: FLOWCHART OF SUBROUTINE VPP

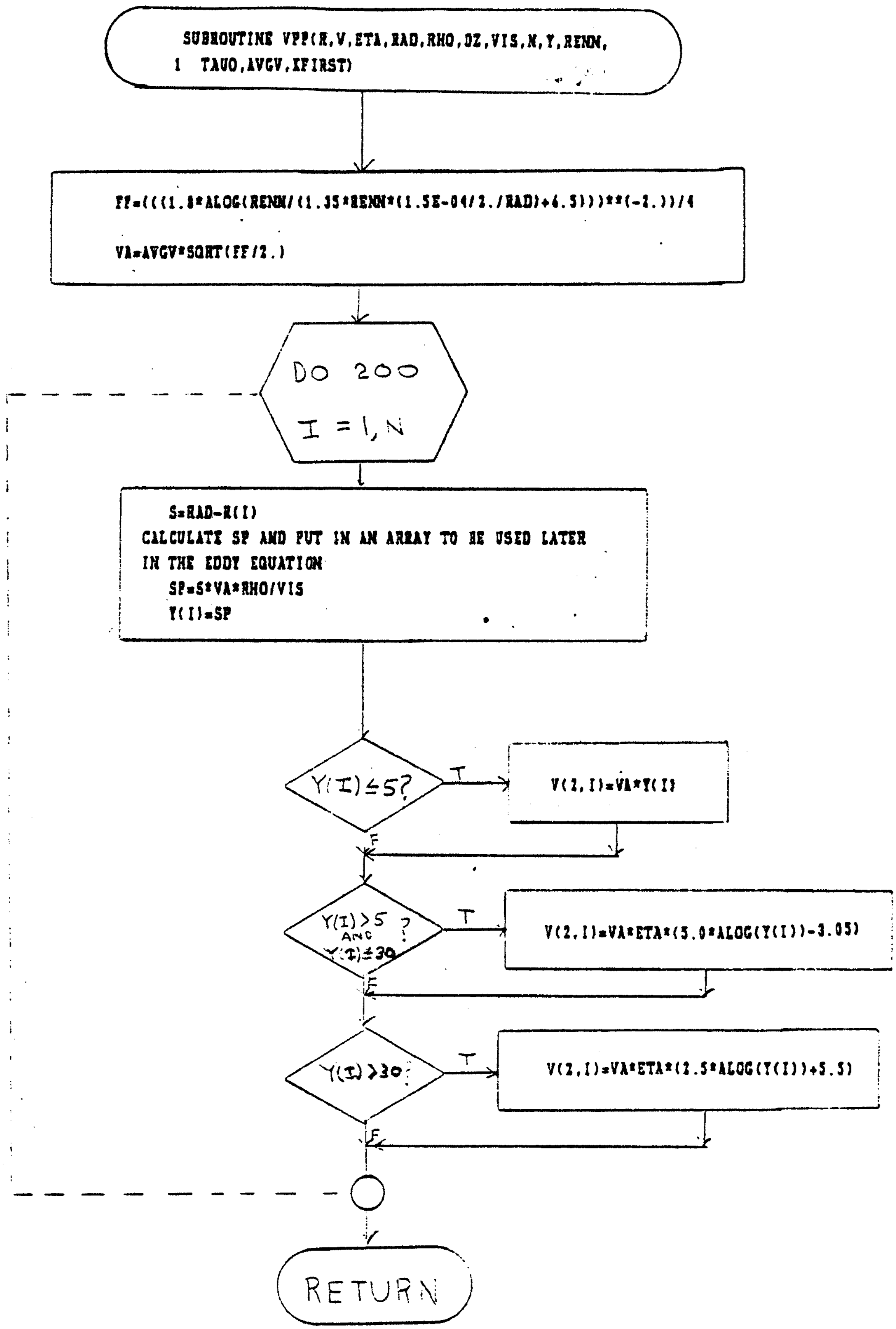


FIGURE 21: FLOWCHART OF SUBROUTINE TRANS

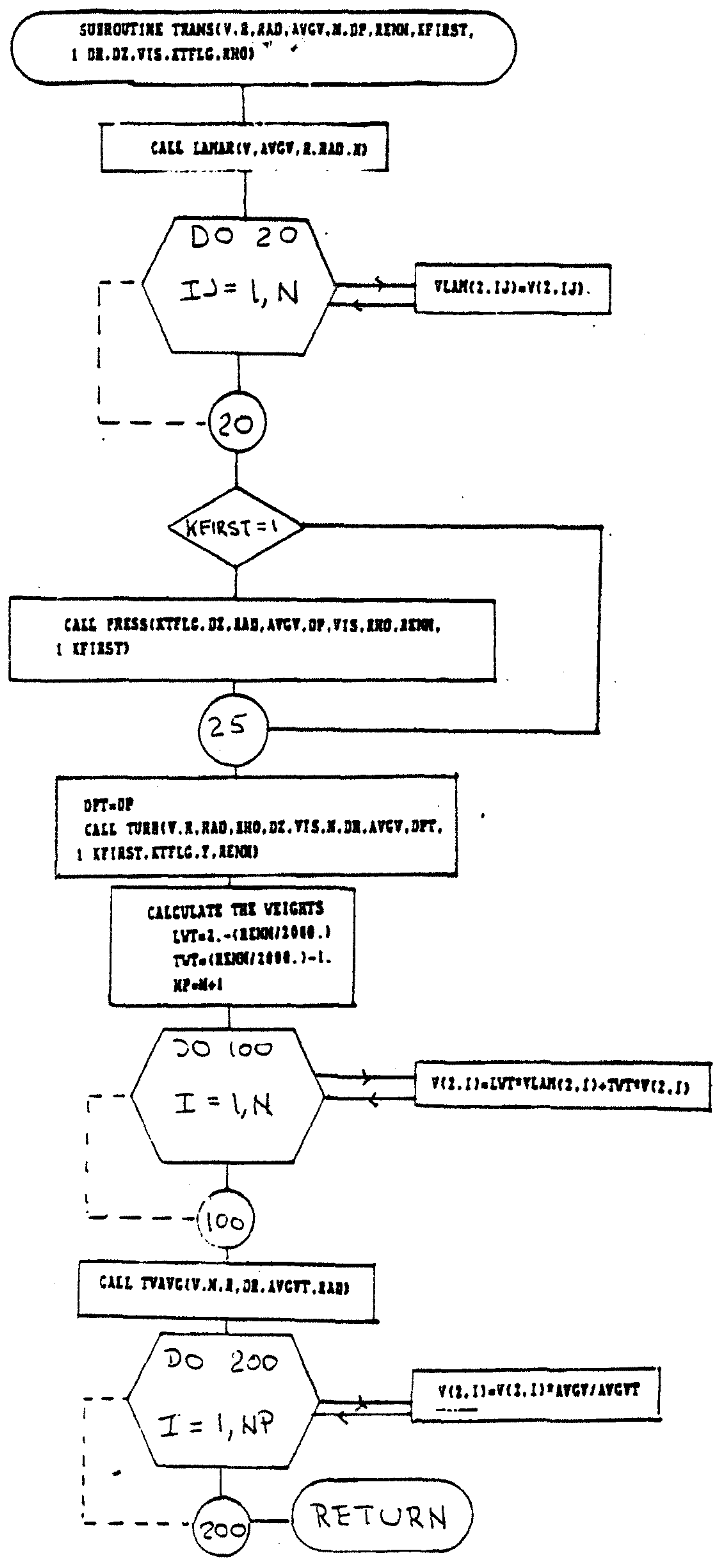


FIGURE 22: FLOWCHART OF SUBROUTINE TEMP

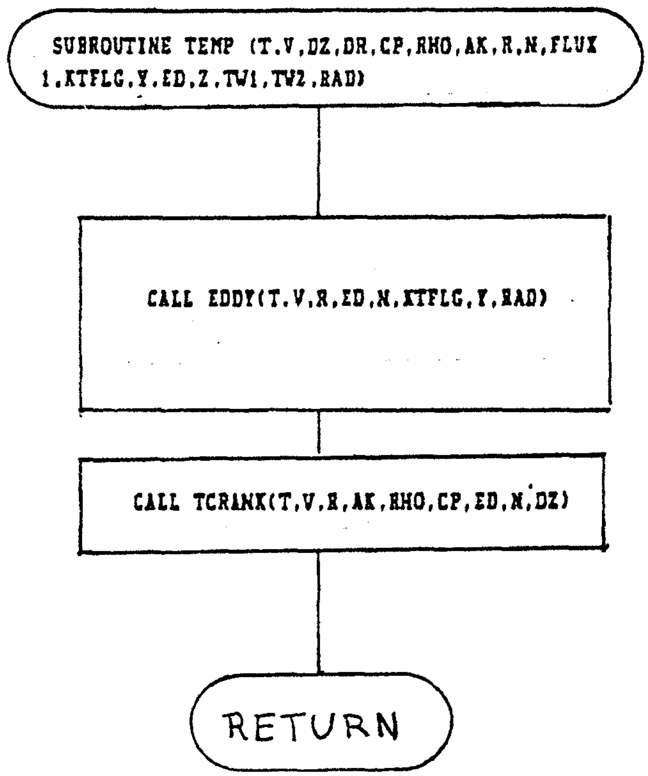


FIGURE 23: FLOWCHART OF SUBROUTINE EDDY

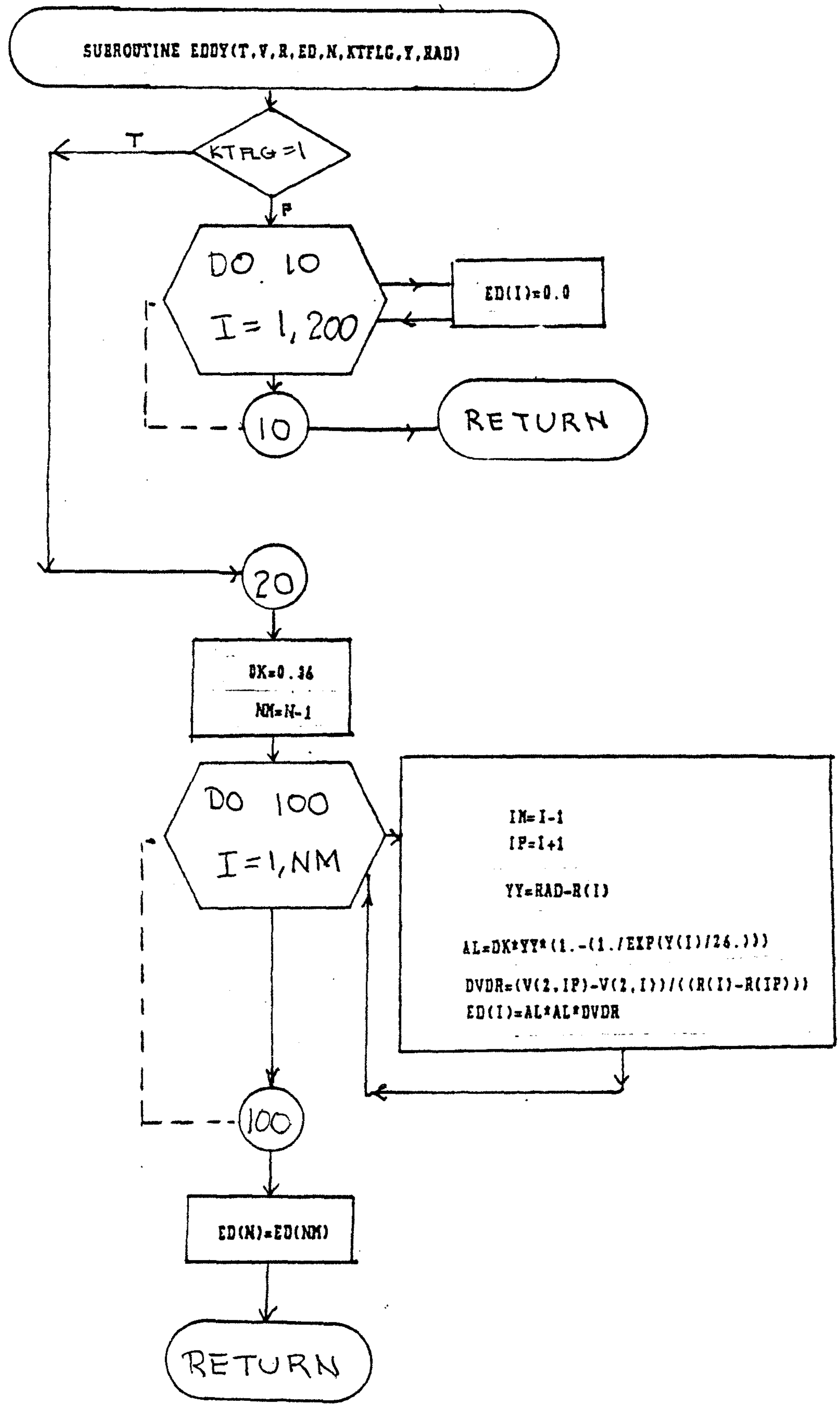


FIGURE 24: FLOWCHART OF SUBROUTINE TCRANK

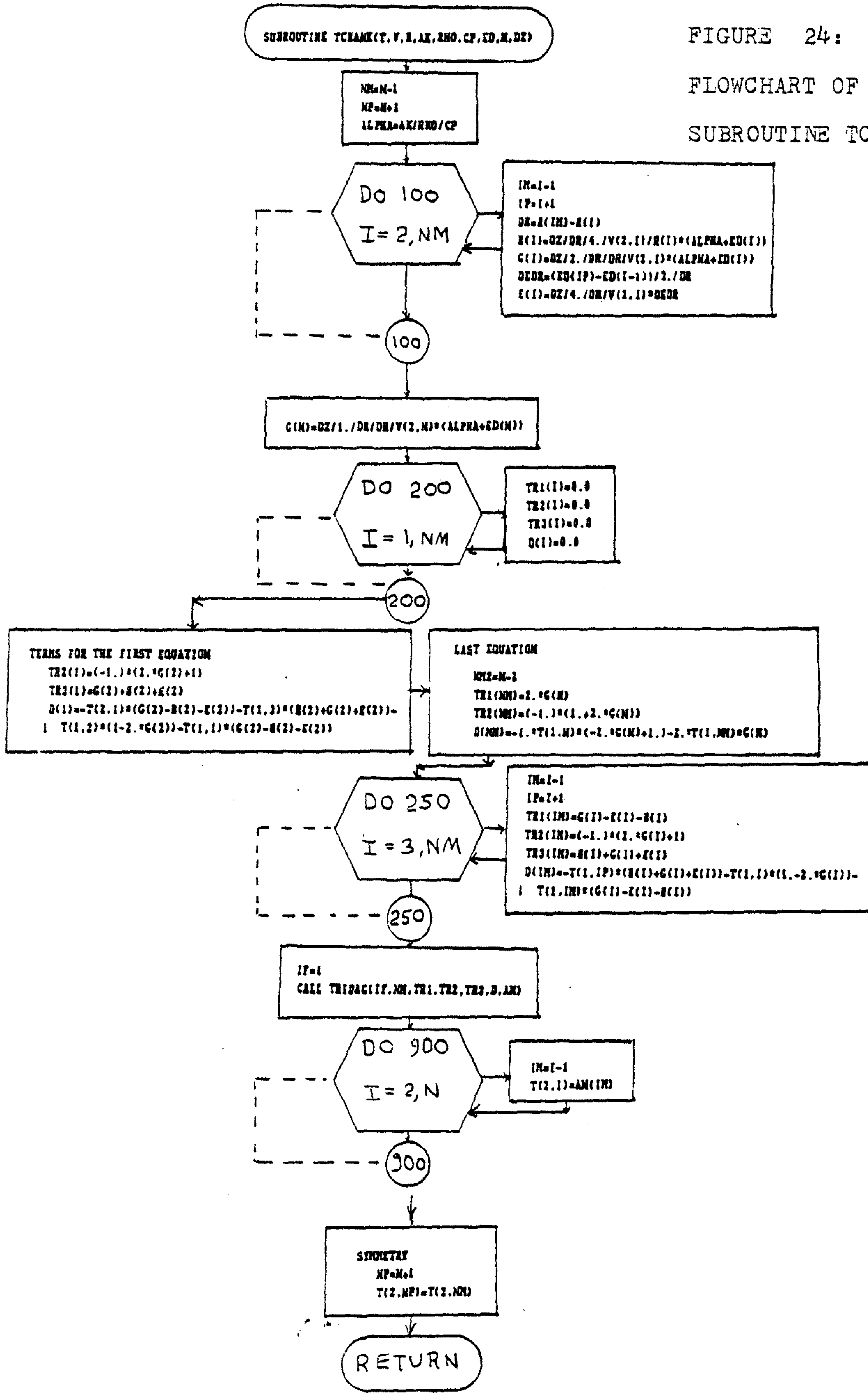


FIGURE 25: FLOWCHART FOR SUBROUTINE TRIDAG

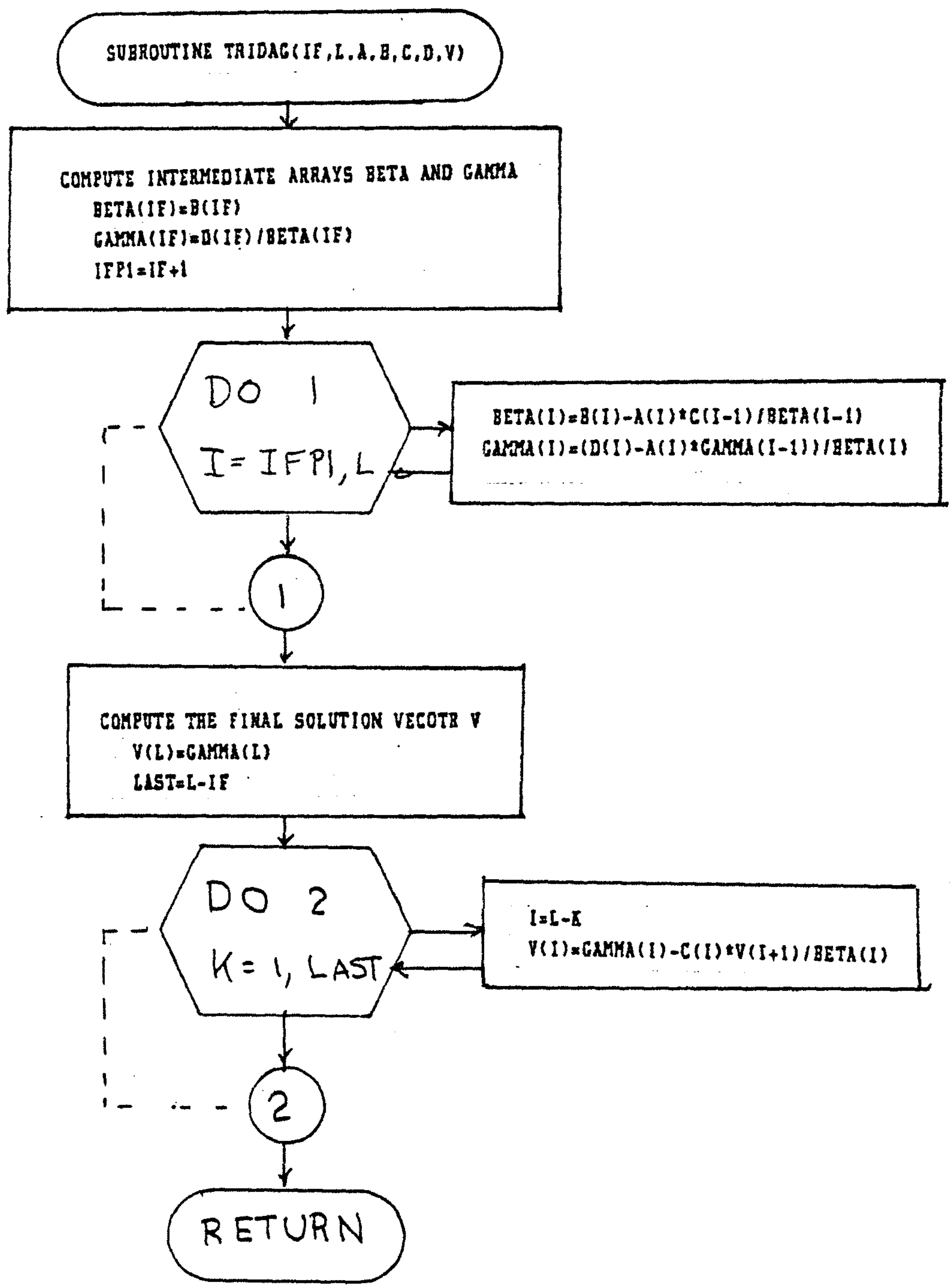


FIGURE 26: FLOWCHART OF SUBROUTINE QCALC

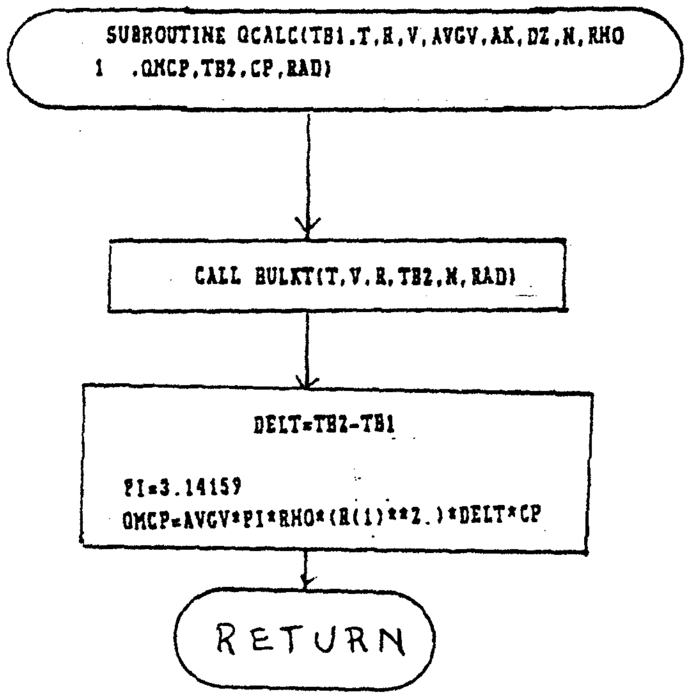


FIGURE 27: FLOWCHART OF SUBROUTINE BULKT

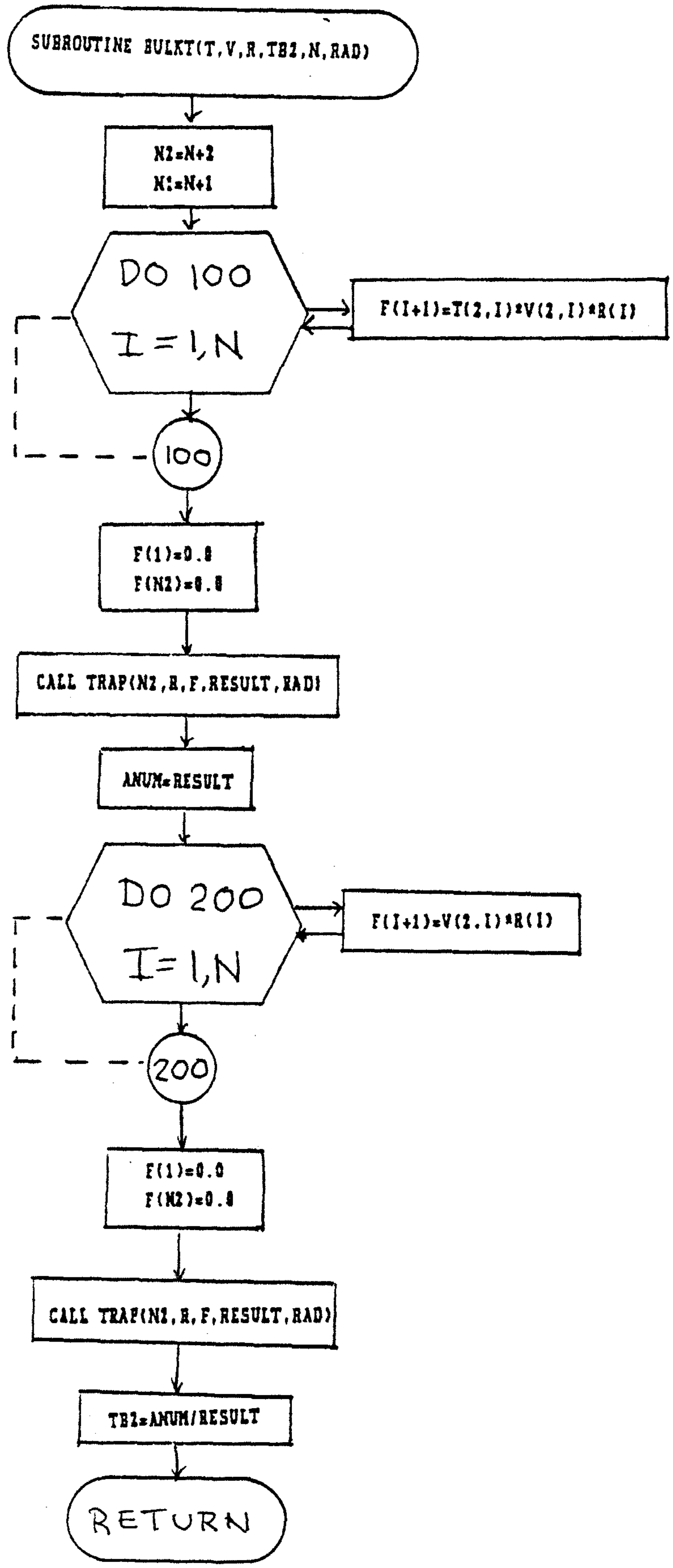


FIGURE 28: FLOWCHART OF SUBROUTINE TADJ

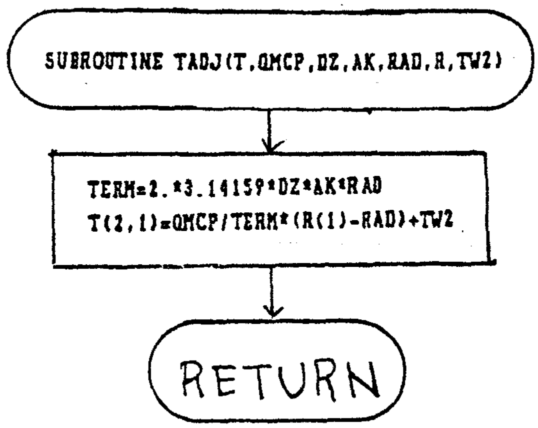


FIGURE 29: FLOWCHART OF SUBROUTINE SKIN

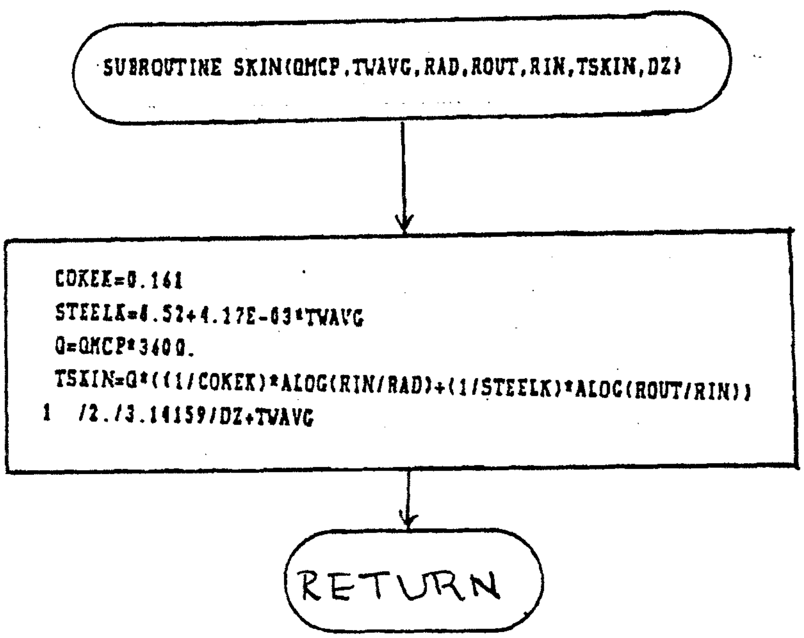


FIGURE 30: FLOWCHART OF SUBROUTINE RESET

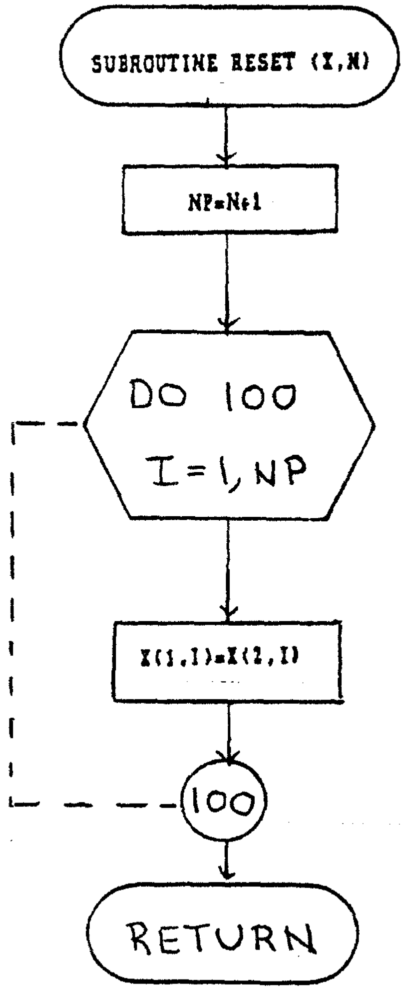
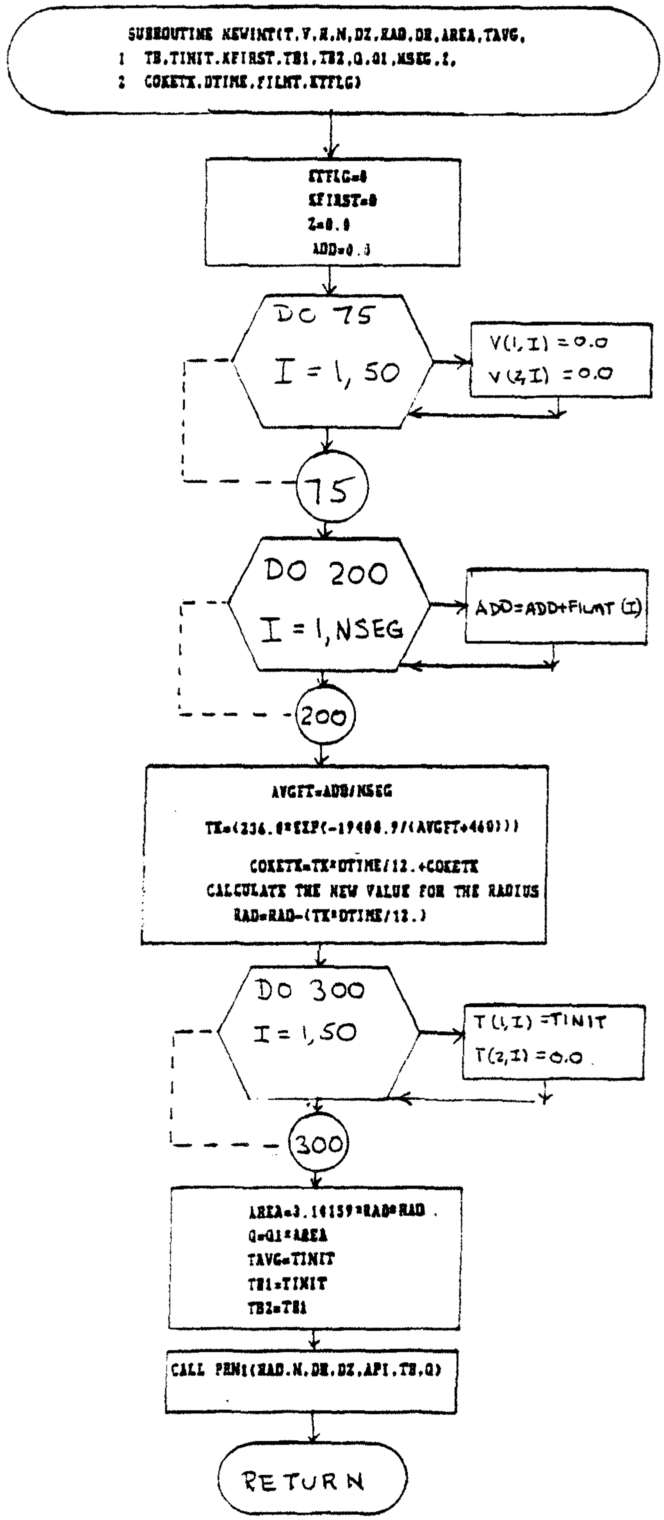


FIGURE 31: FLOWCHART OF SUBROUTINE NEWINT



V. Results and Discussion

The program was executed with the data from Scarborough presented in Table 2. Only data which included initial wall temperatures were used. The data from series A2 and A3, however, were discarded since the wall temperature decreases downstream which is an impossible condition.

The Scarborough data, however, was taken at constant heat flux, and the program uses wall temperature as a boundary condition. An analytical solution could use the heat flux boundary condition very easily, however, the constant heat flux boundary condition poses problems for the numerical analysis. In order to use constant heat flux, and solve equation 18 numerically, one must know the wall temperature or film temperature, and then iterate to determine the correct profile in the laminar sublayer. This method would have posed serious stability problems, and so was not used.

The overall results are presented and compared with Scarborough's in Table 3. Heat flux as a function of tube length, as predicted by the program, is compared with the Scarborough data in Figures 34 through 39. The initial high heat flux predicted by the program, evident in Figures 34 through 39, can be attributed to the initial discontinuity in the temperature profile. Table 3 presents the percent difference between the average heat flux predicted by the program, and the Scarborough data. The difference in values can be attributed to the following:

1. Some of the Scarborough data, as discussed in the introduction, is inconsistent and anomalous. Table 1, for example, presents values from Scarborough which indicate that for constant flow rate, increasing the heat flux decreases the tube temperature. Furthermore, the bulk temperatures, which were reported as constant, actually varied. In one case, for a reported outlet bulk temperature of 684 F the temperature actually varied from 436 F to 715 F. This is an indication that the heat flux was not constant.

2. The expressions for the eddy diffusivity (equations 19 through 21) are empirical. There is no guarantee that these expressions will be accurate for the conditions used by Scarborough. The value of the eddy diffusivity can have a great effect on the bulk temperature and the heat flux.

The values predicted by the program for outlet bulk temperature generally compare within three percent.

At low flow rates (143 lbm/ft2-s) the program predicts the amount of coke within 1.7 percent. At a flow rate of 285 lbm/ft2-s the program and Scarborough differ by, in one case 17 percent, and in another 261 percent. At a flow rate of 430 lbm/ft2-s the program predicts 11×10^{-4} feet of coke, however, Scarborough reports no coke for this data series. The difference is an indication that coking is not just kinetically controlled, but may also be a function of mass transfer and mechanical effects. At higher velocities, some coke may actually scour from the tube wall.

The model presented does not include mass transfer for the following reasons:

1. A literature search revealed no published data on the mass transfer of coke precursors in crude oil.

2. There is not enough data presented by Scarborough to determine the mass transfer coefficient from data.

The velocity profile generated at various points downstream in the tube is shown in Figure 40. The value of the correction factor, η, for the Nikuradse equations (equations 29 and 30) is plotted for a typical series (D4) in Figure 41 as a function of length downstream. Figure 42 is a plot of the log of Reynolds number versus η. This is clearly a linear relationship. Fitting with least squares results in the following equation:

$$\eta = 2.97 - 0.144 \ln(Nre)$$

$$(0.9 < \eta < 1.1 \text{ for } 4X10^{5} < Nre < 1.7X10^{6})$$

The temperature profile at various lengths downstream for series D4 is presented in Figure 43. The dramatic effect of coke is illustrated by comparing Figures 44 and 45 which show temperatures of the outside tube wall with and without coke. Although the model predicts the outside tube wall temperature to be the highest at the entrance of the tube, this may be due to the initial discontinuity in the temperature profile.

The importance of updating the physical properties as the bulk temperature changes is illustrated in Figures 46 and 47 which shows the increase in average velocity, and bulk temperature respectively, as the fluid travels downstream.

The size of the time increment does not have an effect on any of the cases examined. This is a result of the small effect that coking has on the film temperature. Therefore, the fluid temperature profile and coking rate only needs to be calculated at an initial time, and the outside tube temperature can be determined directly from the coking rate and run time.

TABLE 2: THE DATA USED FOR COMAPRISON WITH SCARBOROUGH

Data Name	Bulk Temperature Inlet, F	Mass Flow Rate Lbm/ft2-s	Wall Temperature at 3 ft F	Wall Temperature at 6 ft F
C2	660	285	800	830
D2	650	143	865	980
B3	650	430	805	810
C3	645	285	860	885
D3	640	143	910	920
D4	640	143	820	830

TABLE 3: COMPARISON OF RESULTS

Scarborough

Data Name	Bulk Temperature Out in F	Average Heat Flux in BTU/hr-ft2	Coke Thickness in ft $(X\ 10^{4})$
C2	710	59000	1.9
D2	750	59000	5.8
B3	677	44000	0
C3	684	44000	8.3
D3	720	45000	18.
D4	693	29000	8.8

Program Results

Data Name	Bulk Temperature Out in F	Average Heat Flux in BTU/hr-ft2	Coke Thickness in ft $(X\ 10^{4})$
C2	706	54000	5.2
D2	733	50000	5.9
B3	692	72000	11.
C3	713	78000	30
D3	704	37000	18.
D4	676	21000	8.8

Percent Difference Between Program and Scarborough

Data Name	Bulk Temperature Out	Average Heat Flux	Coke Thickness
C2	-0.6	-8.5	17
D2	-2.3	-15	1.7
B3	2.2	64	N/A
C3	4.4	77	261
D3	-2.2	-17	0
D4	-2.5	-27	0

FIGURE 34: HEAT FLUX COMPARISON FOR SERIES C2

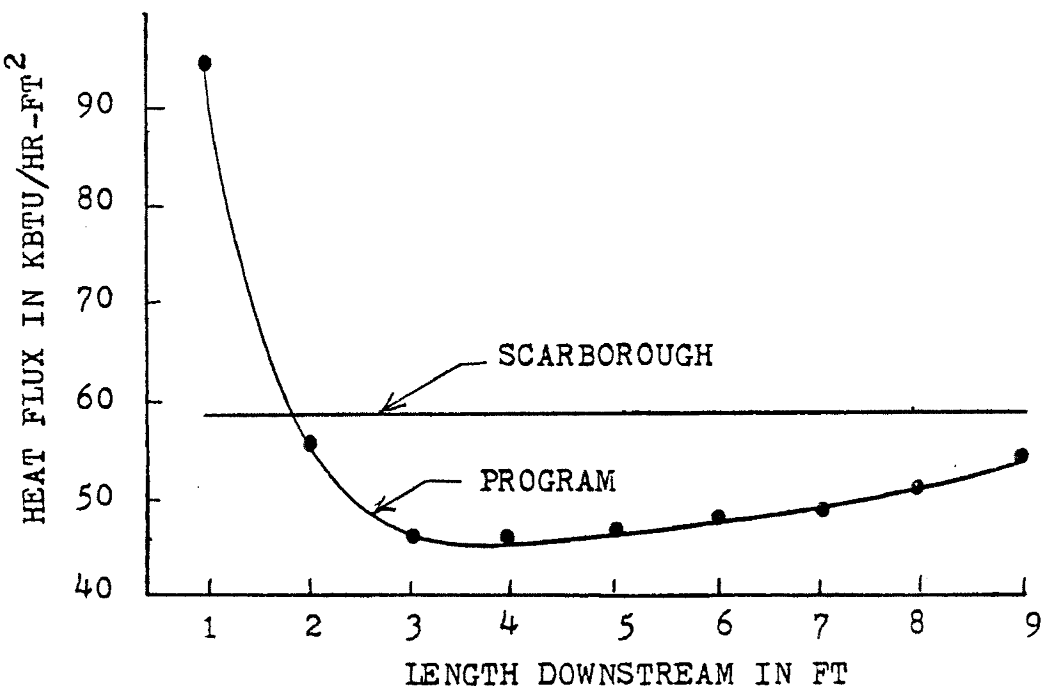


FIGURE 35 : HEAT FLUX COMPARISON FOR SERIES D2

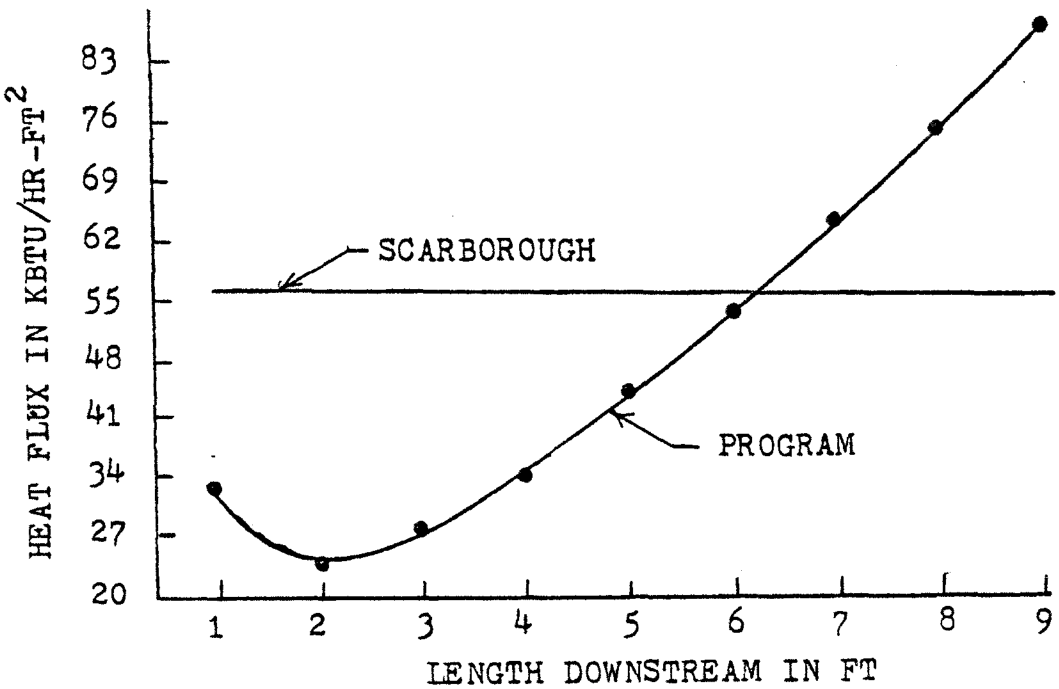


FIGURE 36: HEAT FLUX COMPARISON FOR SERIES B3

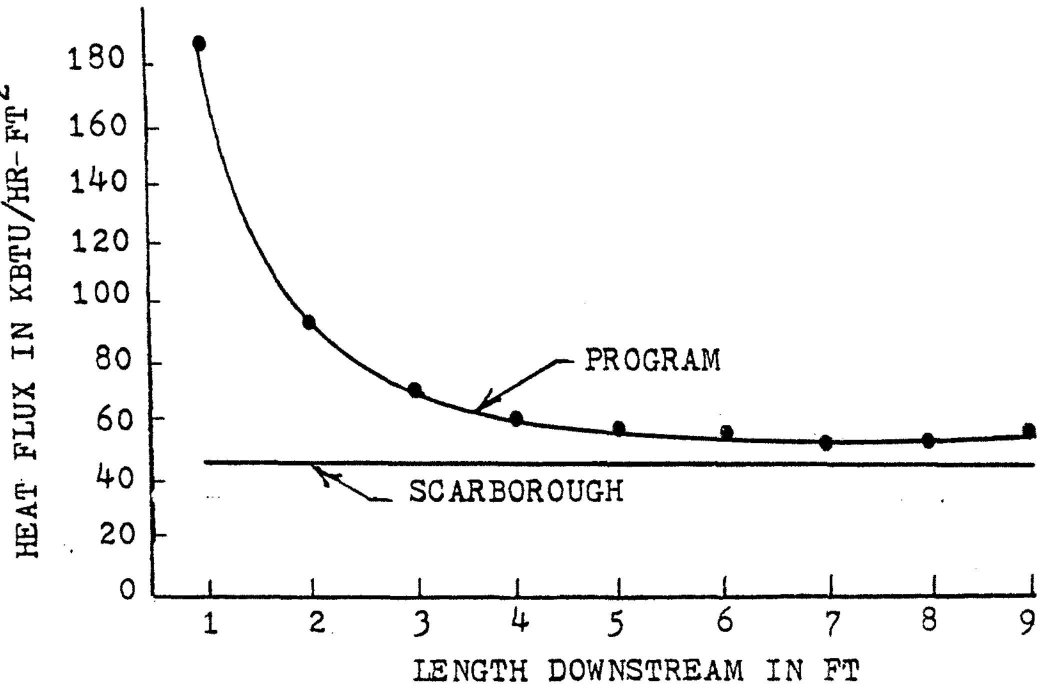


FIGURE 37 : HEAT FLUX COMPARISON FOR SERIES C3

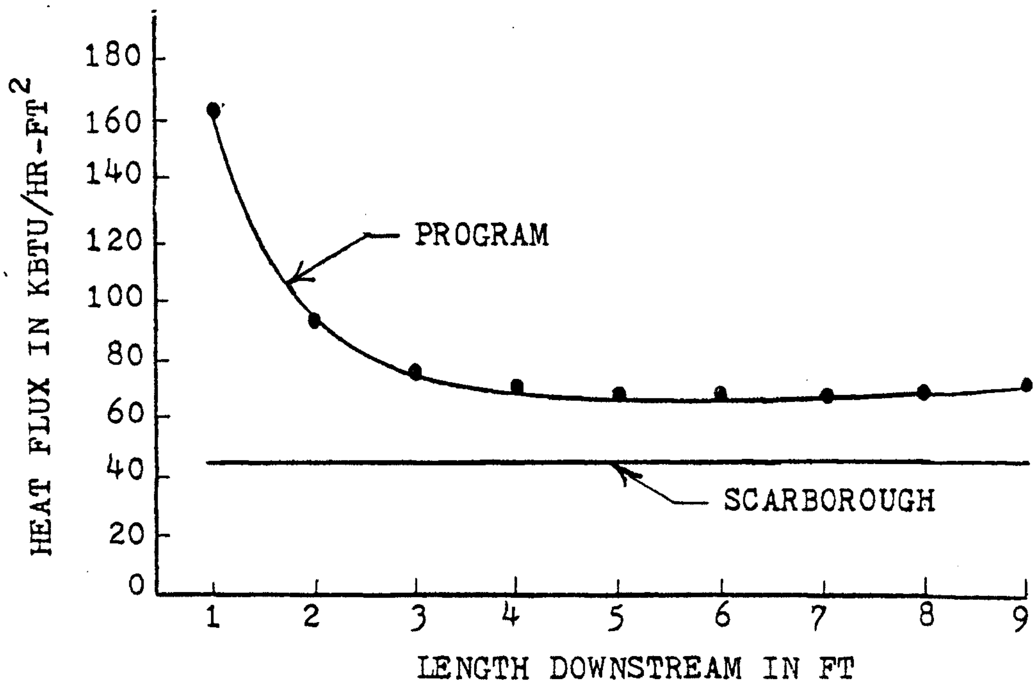


FIGURE 38: HEAT FLUX COMPARISON FOR SERIES D3

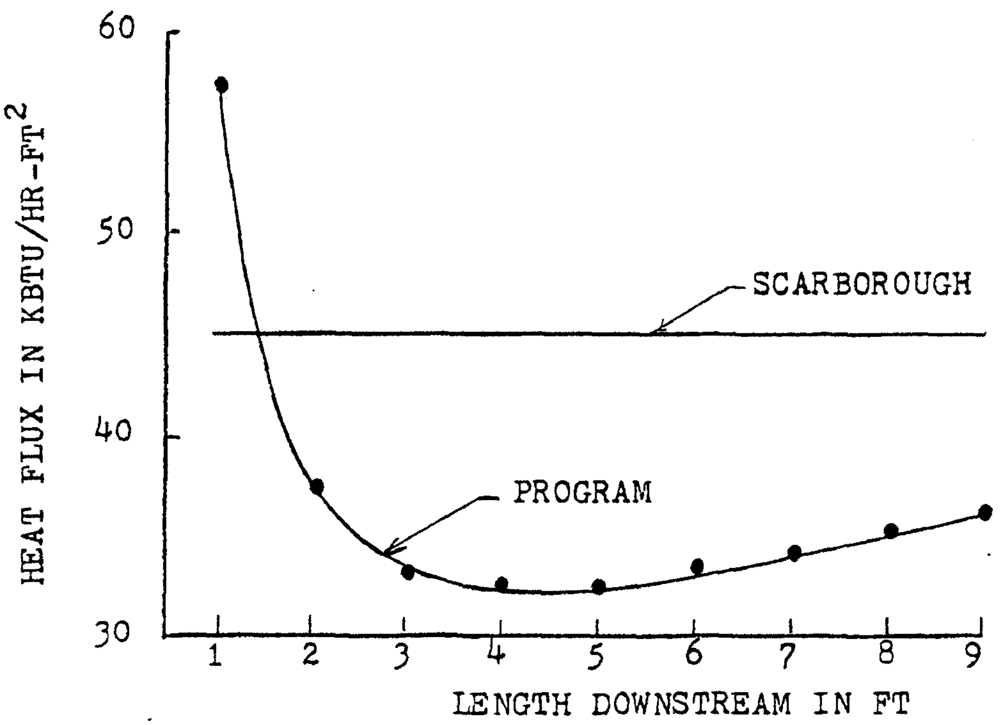


FIGURE 39: HEAT FLUX COMPARISON FOR SERIES D4

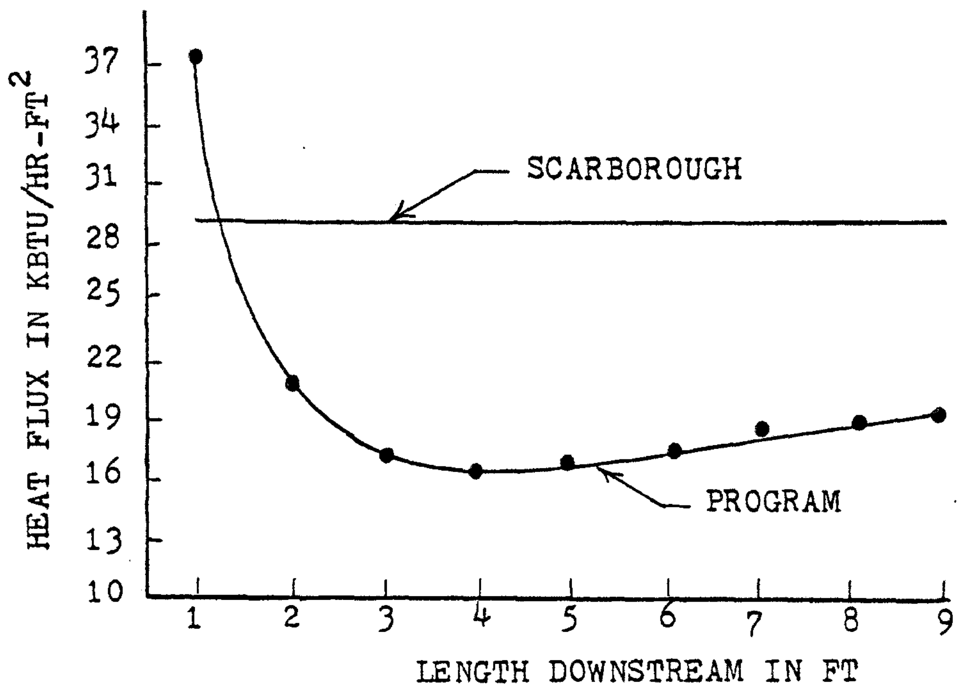


FIGURE 4a VELOCITY PROFILE FOR SERIES D4

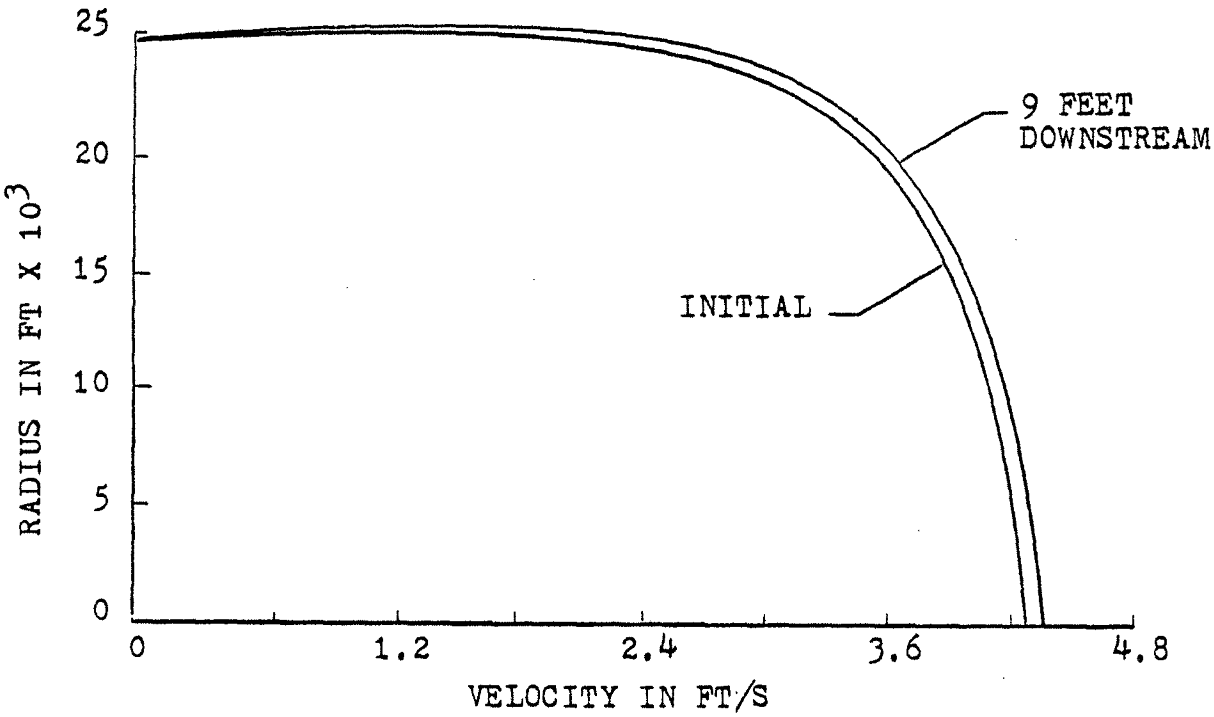


FIGURE 41 : VELOCITY CORRECTION FACTOR FOR SERIES D4

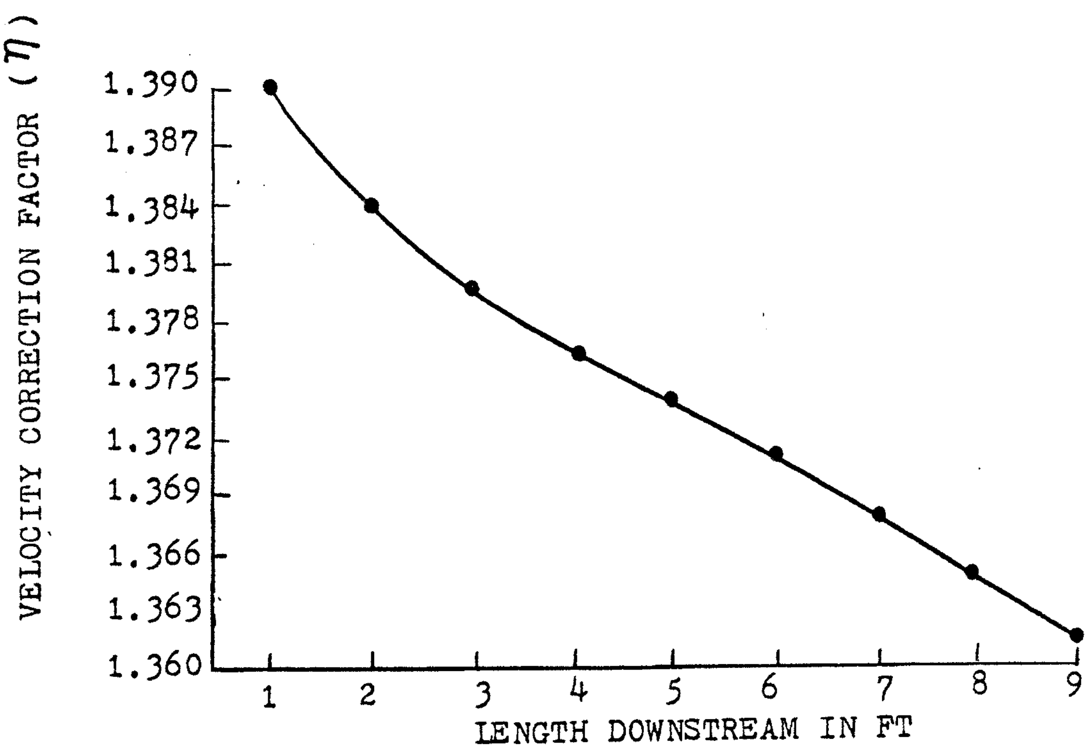


FIGURE 42: VELOCITY CORRECTION FACTOR AND REYNOLDS NUMBER

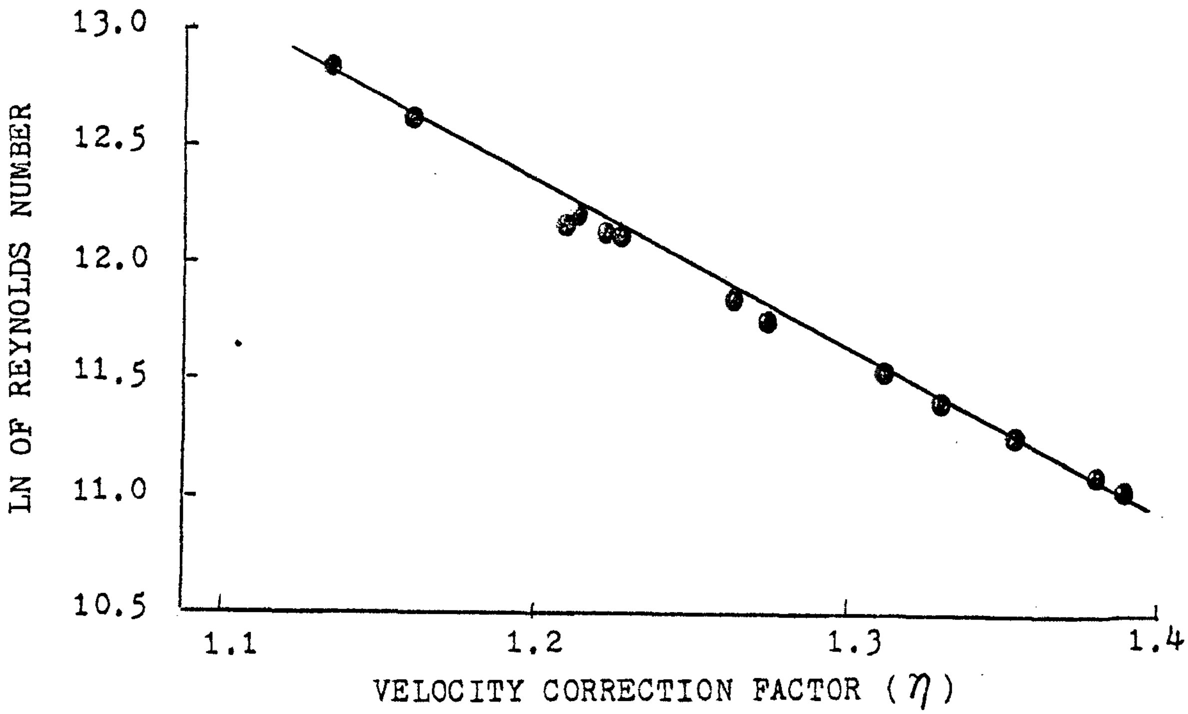


FIGURE 43: TEMPERATURE PROFILE FOR SERIES D4

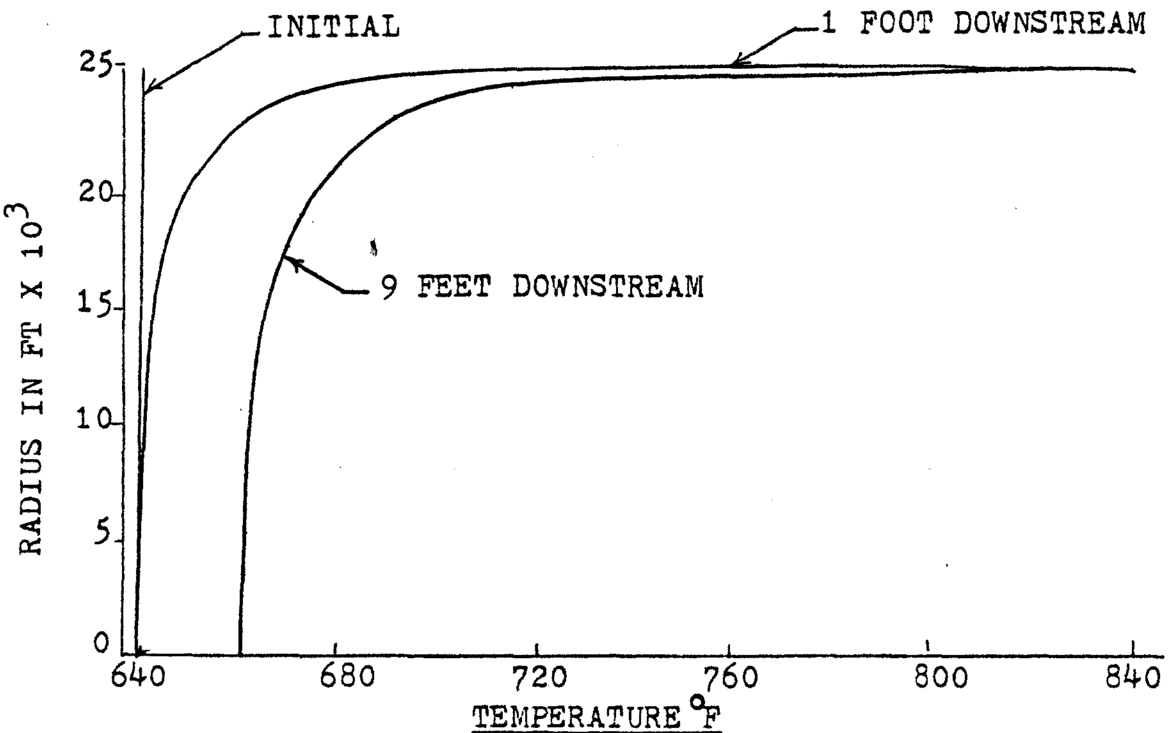


FIGURE 44: TUBE WITHOUT COKE LAYER FOR SERIES D4

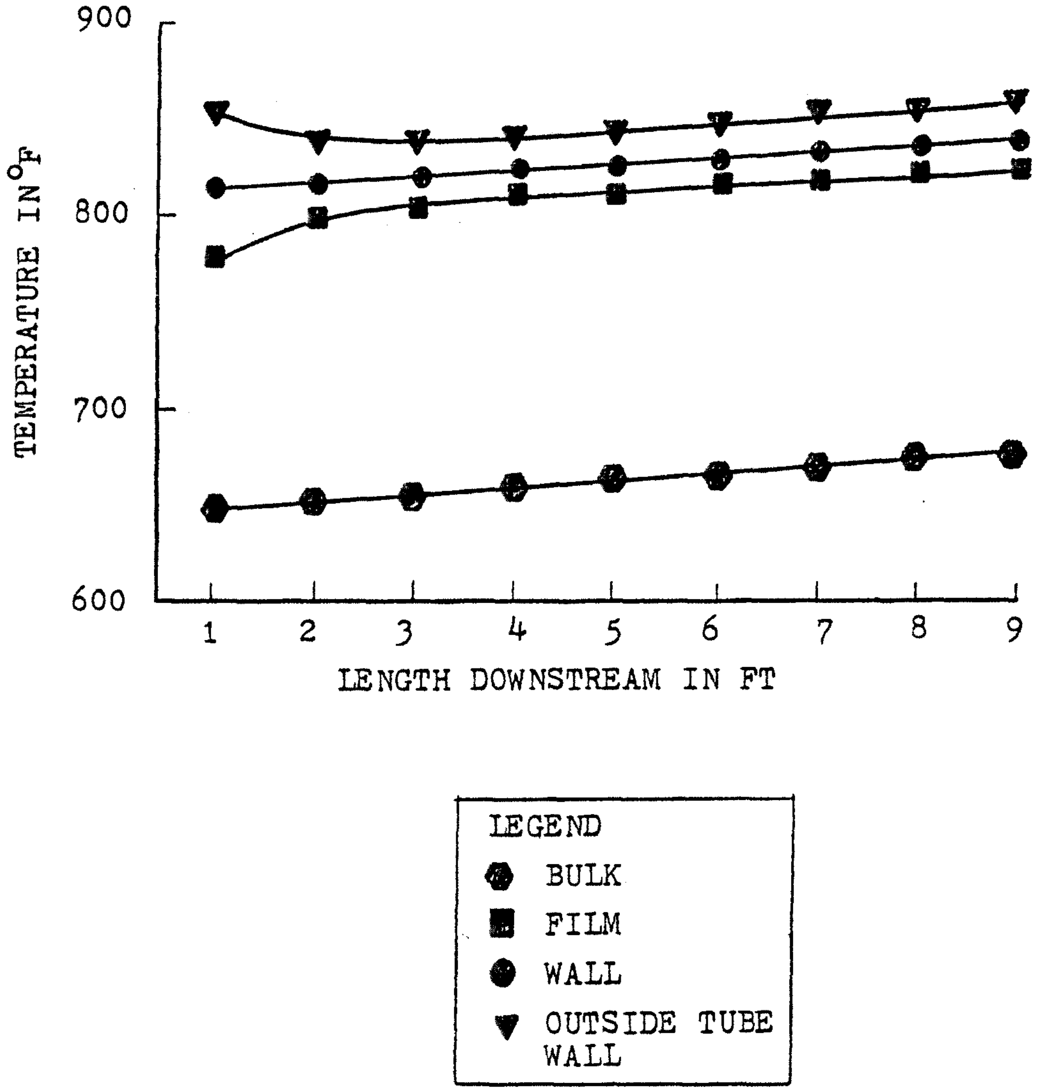


FIGURE 45: TUBE WITH COKE LAYER (0.01 inches) FOR SERIES D4

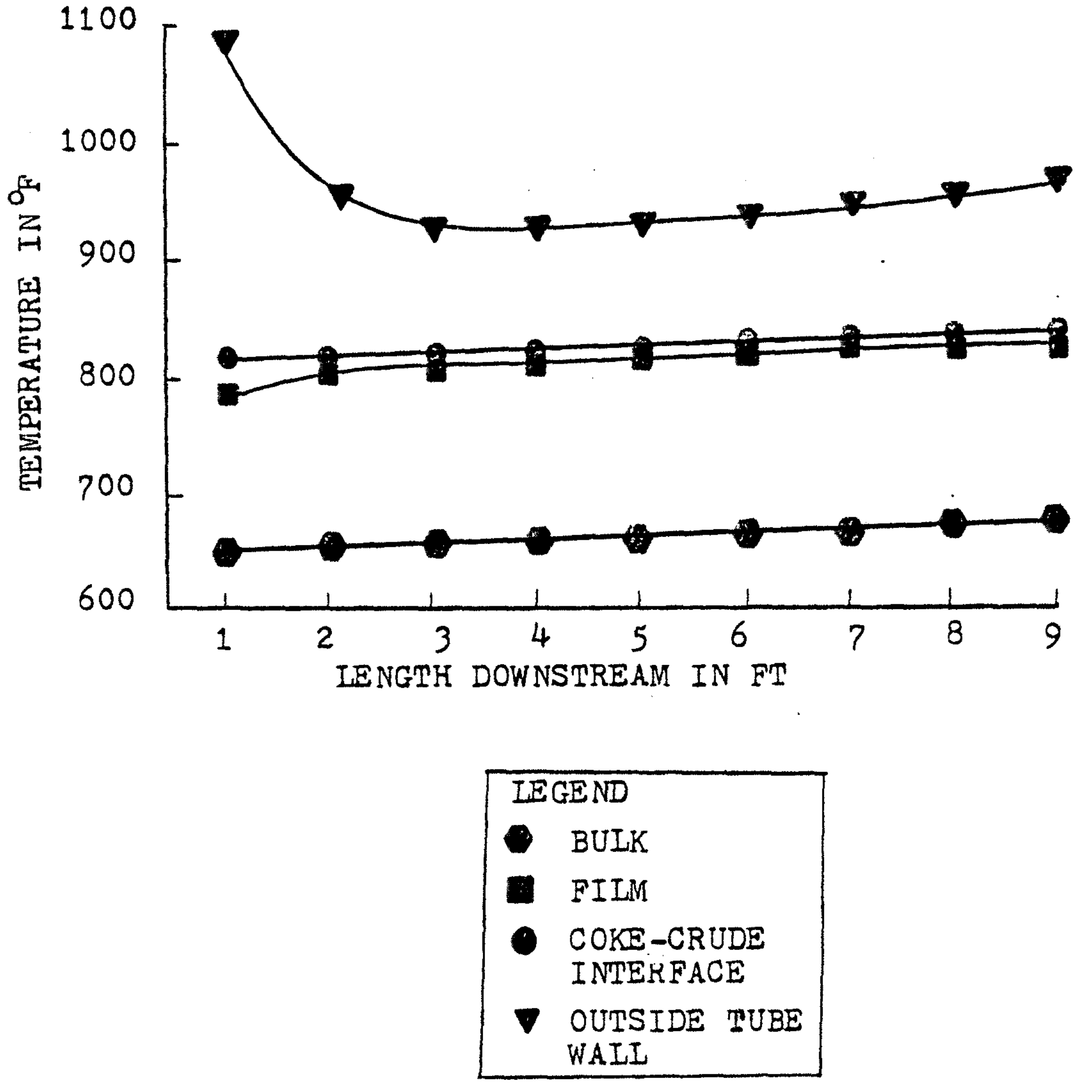
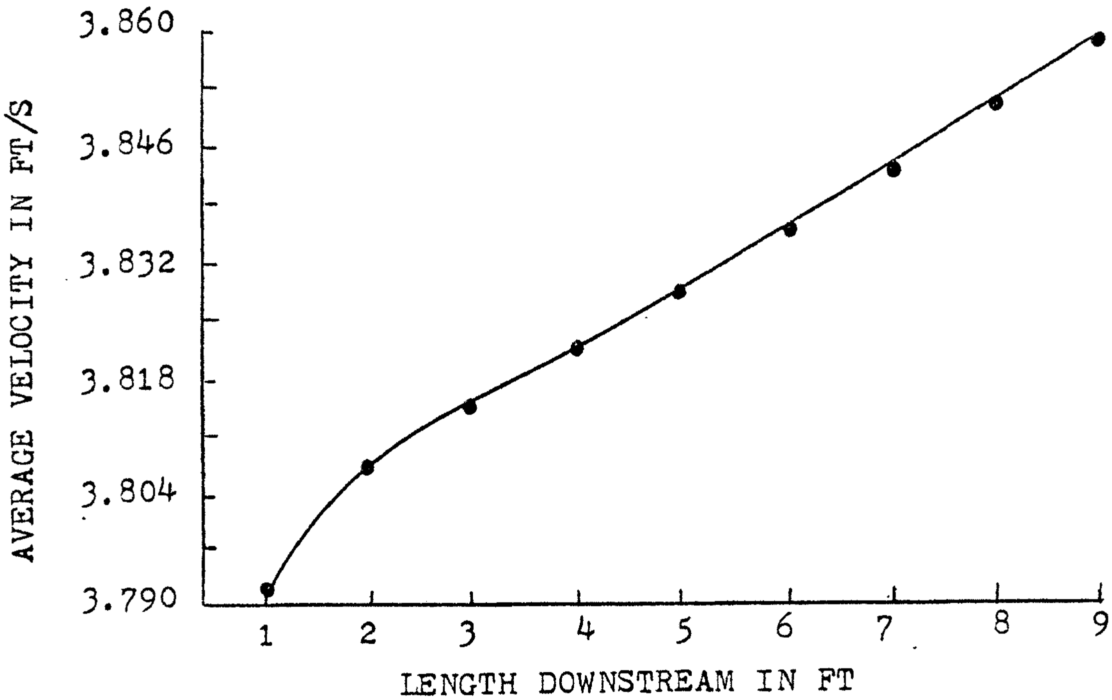


FIGURE 46: AVERAGE VELOCITY FOR SERIES D4



VI. Conclusions

Coking of furnace tubes by crude oil was modeled from an analytical standpoint. To the author's knowledge no analytical equations exist which accomplish this. The major consideration of this model was to obtain the temperature of the laminar sublayer as accurately as possible since this is where the coking reaction is believed to occur (12). The temperature profile of crude oil as it passes through a furnace tube was modeled by solving the transport equations by the Crank-Nicolson method. Internal checks are in the program to ensure closure of the mass and heat balances. The program requires the wall temperature to be specified at two points, but does not require the temperature to be constant.

This model appears to work well at low flow rates. However, since there are very little published data available, the model cannot be given a complete test. The model does not perform well at high flow rates, when transfer of coke from the wall back to the bulk fluid may occur.

VII. Recommendations

1. Clearly there is a need for useful data on coking. The data should include accurate measurements of tube wall temperature, bulk temperature, actual coke thickness along the entire length of the tube, and the presence of coke in the outlet oil.
2. Actual industrial conditions such as heating the crude from ambient temperatures should be used.
3. The coking characteristics of different types of crude oil should be studied.
4. The mathematical model presented here should include mass transfer terms. Once enough data is available the mass transfer terms could be evaluated.
5. The actual kinetics involved with coking should be studied, including the catalytic effect of the tube wall.

Nomenclature

A - Term in the viscosity equation

API - API gravity

B - Term in the viscosity equation

C - Characterization factor

Cp - Heat capacity, BTU/lbm-F

E - Coking activation energy

f - Fanning friction factor

G - function used in secant method

k - thermal conductivity, BTU/hr-ft-F

ℓ - Prandtl mixing length, ft.

L - Length, ft

m - Mass flow rate, lbm/s

Nre - Reynolds number, dimensionless

P - Pressure drop, lbm/ft-s2

q - Heat flux, BTU/s-ft-F

r - Radial coordinate

R - Radius of flow, ft

r - Radial increment, ft

T - Temperature, F

Tbulk- Bulk temperature, F

Tc - Temperature at coke-crude oil interface, F

Tf - Temperature of the laminar sublayer, F

Ts - Temperature of the outside wall of the tube, F

Tw - Temperature of the inside wall of the tube, F

Tb - Mid boiling point of crude oil, F

Vz - Velocity in z direction, ft/s

$\overline{Vz}$ - Time-smoothed velocity in the z-direction (in turbulent flow), ft/s

$\langle Vz \rangle$ - Average velocity, ft/s

$$V^* = \sqrt{\frac{\tau_o}{\rho} g_c}$$

$$Y = \frac{(R-r)\, V^* \rho}{\mu}$$

z - axial increment, ft

GREEK NOTATION

$$\alpha = \frac{k}{\rho C_p}$$

Γ - Value of Y at the buffer layer-core interface

$$\gamma_M = \frac{\Delta Z}{2(\Delta r)^2}\left(\frac{\alpha_M + \epsilon_{H_M}}{V_{z_M}}\right)$$

$$\gamma_M' = \Delta Z\left(\frac{\alpha + \epsilon_H}{(\Delta r)^2 V_z}\right)$$

ϵ - Roughness factor, ft

ϵ_H - Thermal eddy diffusivity, ft2/s

ϵ_M - Momentum eddy diffusivity, ft2/s

μ - Viscosity, lbm/ft-s

$$\beta_M = \left(\frac{\Delta Z}{4 \Delta r}\right)\left(\frac{\alpha_M + \epsilon_{HM}}{V_{z_M} r_M}\right)$$

ρ - Density, lbm/ft3

τ_o - Shear stress at the tube wall, lbm/s2-ft

$$\xi_M = \frac{\Delta Z}{4 \Delta r\, V_{z_M}} \left(\frac{\partial \epsilon_H}{\partial r}\right)_M$$

SUBSCRIPTS

n - denotes axial direction

m - denotes radial direction

References

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APPENDIX A

LISTING OF THE COMPUTER PROGRAM

(THE VARIABLE DICTIONARY IS ON THE LAST PAGES OF THE PROGRAM)

```
C**********************************************************
C**********************************************************
C*****                                               *****
C*****      COKING PROGRAM BY                        *****
C*****      JOE POLIMENI                             *****
C*****                                               *****
C*****      FOR PARTIAL FULFILMENT OF                *****
C*****      REQUIREMENTS OF MASTER OF SCIENCE        *****
C*****      IN CHEMICAL ENGINEERING AT NJIT          *****
C*****                                               *****
C*****      JULY  7, 1983                            *****
C*****                                               *****
C**********************************************************
C**********************************************************
C
C
C
C
C
C
      DIMENSION V(2,50), T(2,50), R(50)
      DIMENSION ED(50),Y(50),FILMT(100),IPRN(200)
C
C
C
C *** INIT IS A SUBROUTINE WHICH DOES THE FOLLOWING
C     1) INITIALIZES THE FLAGS
C     2) SETS VARIABLES TO ZERO
C     3) CALL SUBROUTINE READER WHICH READS
C        IMPORTANT DATA
C     4) CALLS SUBROUTINE PRN1 WHICH PRINTS
C        IMPORTANT DATA
C
      CALL INIT(T,V,R,N,Q,Q1,DZ,RAD,DR,AREA,TAVG,API,
     1  TB,HFLUX,FLUX,TINIT,KFIRST,KTFLG,TB1,TB2,NSEG,Z,
     2  TC3,TC6,DTIME,TTIME,COKETK,TIME,IPRN,NPRN,ROUT,RIN,
     3  IP)
 50   CONTINUE
C
C *** BEGIN A LOOP WHICH COUNTS THE Z INCREMENT
C     NSEG IS THE NUMBER OF Z SEGMENTS
C
           DO 200 I=1,NSEG
C
C *** PHYP IS A SUBROUTINE WHICH CALCULATES:
C     1) THE PHYSICAL PROPERTIES OF THE CRUDE
C        OIL BASED ON TAVG
C     2) THE AVERAGE VELOCITY AND REYNOLDS NUMBER
C     3) THE THICKNESS OF THE LAMINAR SUB LAYER
C     4) THE RADIAL POSITIONS
```

```
C
      CALL PHYP(TAVG,API,AREA,Q,AK,RHO,CP,AVGV,
     1  HFLUX,FLUX,DZ,N,R,VIS,TB,RENN,RAD,THICK,TAUO)
C
C
C
C  INCREMENT THE LENGTH
      Z=Z+DZ
C
C  RESET NEW BULK TEMPERATURE TO OLD BULK TEMPERATURE
      TB1=TB2
C
C *** WALL T IS A SUBROUTINE WHICH ASSIGNS
C     THE WALL TEMPERATURE TO EACH Z INCREMENT
C
      CALL WALLT(TW1,TW2,T,Z,DZ,TC3,TC6,TWAVG)
C
C *** RENVL IS A SUBROUTINE WHICH CALLS THE PROPER
C     VELOCITY PROFILE SUBROUTINE FOR THE
C     REYNOLDS NUMBER OF INTEREST
C
      CALL RENVL(VIS,AVGV,RAD,RHO,RENN
     1   ,V,R,N,KFIRST,DR,DZ,KTFLG,Y,TAUO)
C
C
C *** TEMP IS A SUBROUTINE WHICH CALLS THE
C     SUBROUTINE TO CALCULATE THE EDDY DIFFUSIVITY
C     AND CALLS THE SUBROUTINE WHICH CALCULATES THE
C     TEMPERATURE PROFILE
C
  999 CALL TEMP(T,V,DZ,DR,CP,RHO,AK,R,N,FLUX
     1,KTFLG,Y,ED,Z,TW1,TW2,RAD)
C
C
C *** QCALC IS A SUBROUTINE WHICH DOES TWO THINGS:
C     1) IT CALLS A SUBROUTINE 'BULKT'
C        WHICH CALCULATES THE BULK TEMPERATURE
C     2) IT CALCULATES Q BY M*CP*DELTA T
C
      CALL QCALC(TB1,T,R,V,AVGV,AK,DZ,N,RHO
     1   ,QMCP,TB2,CP,RAD)
      TAVG=TB1
      BTOL=.1
      TH=T(2,1)
C
C  FIND OUT WHAT T NEXT TO THE WALL SHOULD HAVE BEEN
      CALL TADJ(T,QMCP,DZ,AK,RAD,R,TW2)
C
C  SAFETY SO THAT THE RADIAL SEGMENT NEXT TO THE
C  WALL DOES NOT STAY THE WALL TEMPERATURE
C  MAKING IT THE WALL TEMPERATURE IS ONLY DONE TO
C  INCREASE THE SPEED OF CONVERENGENCE
      CHECK=ABS(T(2,1)-TH)
      IF(CHECK.GT.BTOL) GO TO 999
```

```
C
C
C  CALL THE SUBROUTINE TO DETERMINE THE SKIN TEMPERATURE
       CALL SKIN(QMCP,TWAVG,RAD,ROUT,RIN,TSKIN,DZ)
C *** RESET IS A SUBROUTINE WHICH SHIFTS ARRAYS SUCH
C      THAT THE NEW VALUES WILL BECOME THE NEXT INCREMENT'S
C      OLD VALUES
C
C *** PRN2 IS A SUBROUTINE WHICH PRINTS THE RADIAL VALUES
C      THE VELOCITY, TEMPERATURE, AND EDDY DIFFUSIVITY
C      FOR EACH Z SEGMENT
C
C
C  PRINT DECISION
       DO 901 J=1,NPRN
       IF (IP.EQ.IPRN(J)) CALL PRN2(V,T,R,TB1,TB2,RHO,CP
     1,AK,AVGV,RENN,Z,VIS,N,I,ED,Q,OLDT,DZ,RAD,THICK,
     2 TIME,QMCP,TSKIN,TW1,TW2)
 901   CONTINUE
C
 555   CONTINUE
C  PUT THE FILM TEMPERATURE INTO THE ARRAY FILMT
       FILMT(I)=T(2,1)
C
C
       CALL RESET (T,N)
       CALL RESET (V,N)
C
C  THE FIRST TIME HAS ALREADY BEEN ACCOMPLISHED
       KFIRST=1
C
 200   CONTINUE
C
C INCREMENT THE TIME
       TIME=TIME+DTIME
C
C
C  INCREMENT THE PRINTER FLAG
       IP=IP+1
C CHECK TO SEE IF TTIME (THE TOTAL TIME) HAS BEEN REACHED
C IF IT HAS END
       IF(TIME.GT.TTIME) GO TO 111
C
C *** THE COMPLETE LENGTH HAS BEEN COMPLETED ***
C      COKE IS LAYERED ON THE TUBE AND THE PROCESS IS
C      REPEATED
C
       CALL NEWINT(T,V,R,N,DZ,RAD,DR,AREA,TAVG,
     1  TB,TINIT,KFIRST,TB1,TB2,Q,Q1,NSEG,Z,
     2  COKETK,DTIME,FILMT,KTFLG,TC3,TC6,TIME)
C
       GO TO 50
C
 111   CONTINUE
```

```
      STOP
      END
C
C
      SUBROUTINE INIT (T,V,R,N,Q,Q1,DZ,RAD,DR,AREA,TAVG,API,
     1  TB,HFLUX,FLUX,TINIT,KFIRST,KTFLG,TB1,TB2,NSEG,Z,
     2  TC3,TC6,DTIME,TTIME,COKETK,TIME,IPRN,NPRN,ROUT,RIN,
     3  IP)
C
C  THIS SUBROUTINE INITIALIZES IMPORTANT VARIABLES,
C  FLAGS AND CALLS 'READER' WHICH READS IN IMPORTANT
C  DATA FROM A FILE
C
      DIMENSION T(2,50),V(2,50),R(50),IPRN(200)
C
C
C  KFIRST IS THE FLAG WHICH INDICATES WHETHER IT IS THE
C  FIRST TIME THROUGH THE PROGRAM A VALUE OF 0 INDICATES
C  THAT IT IS THE FIRST TIME A VALUE OF 1 INDICATES THAT
C  THAT IT HAS ALREADY GONE THROUGH ONE DZ SEGMENT
      KFIRST=0
C
C  KTFLG IS THE FLAG WHICH INDICATES LAMINAR OR
C  TURBULENT FLOW (0 FOR LAMINAR 1 FOR TURBULENT)
C  IT IS INITALLY SET TO ZERO
      KTFLG=0
C
C
C  Z IS THE LENGTH DOWNSTREAM INITIALLY SET TO 0 FT
      Z=0.0
C
C  SET THE TIME TO ZERO
      TIME=0.0
C
C  SET THE PRINT COUNTER TO ZERO
      IP=0
C
C  THE INITIAL COKE THICKNESS IS ZERO
      COKETK=0.0
C
C  CALL THE PROGRAM WHICH READS THE DATA
      CALL READER(TINIT,TWALL,Q1,NF,RAD,API
     1 ,TB,HFLUX,NSEG,DZ,TC3,TC6,DTIME,TTIME,
     2  IPRN,NPRN,ROUT,RIN)
C
C  CONVERT THE RIN AND ROUT TO FEET
      RIN=RAD/12.
      ROUT=ROUT/12.
C  SET THE VELOCITY MATRIX TO ZERO
       DO 75 I=1,50
        V(1,I)=0.0
        V(2,I)=0.
 75     CONTINUE
      RAD=RAD/12.
```

```
C
      N=NF+1
C
C  INITIALIZE THE TEMPERATURE MATRIX TO TINIT
C
      DO 300 I=1,50
          T(1,I)=TINIT
 300  CONTINUE
C
C
C     CALCULATE CROSS SECTIONAL AREA
      AREA=3.14159*RAD*RAD
C
C  CALCULATE THE FLOW RATE FROM LLBM/FT^2 S TO LBM/S
      Q=Q1*AREA
C
C  THE INITIAL AVERAGE TEMP IS TINIT
C
      TAVG=TINIT
      TB1=TINIT
      TB2=TB1
C
C *** PRN1 IS A SUBROUTINE WHICH PRINTS OUT IMPORTANT
C     INFORMATION WHICH DOES NOT CHANGE FOR EACH
C     INCREMENT
C
      CALL PRN1(RAD,N,DR,DZ,API,TB,Q,TC3,TC6,
     1  DTIME,TTIME)
      RETURN
      END
C
C
      SUBROUTINE READER(TINIT,TWALL,Q,NF,RAD,API
     1 ,TB,HFLUX,NSEG,DZ,TC3,TC6,DTIME,TTIME,
     2  IPRN,NPRN,ROUT,RIN)
      DIMENSION IPRN(200)
C
C  THIS ROUTINE READS IMPORTANT DATA
C
C  THIS ROUTINE IS CALLED BY SUBROUTINE INIT
C
C
C  READ THE INITIAL TEMPERATURE
      READ(5,100) TINIT
C
C  READ THE FLOW RATE IN LBM/FT^2 SEC
      READ(5,100) Q
C
C  READ THE NUMBER OF RADIAL SEGMENTS
      READ(5,200) NF
C
C  READ THE RADIUS IN INCHES
      READ(5,250) RAD
C
```

```
C  READ THE API GRAVITY
      READ(5,250) API
C
C  READ THE TB VALUE
      READ(5,250) TB
C
C  READ THE OUTSIDE WALL RADIUS
      READ(5,250) ROUT
C
C  READ THE NUMBER OF Z SEGMENTS IN ONE PASS
      READ(5,300) NSEG
C
C  READ THE VALUE OF DZ
      READ(5,350) DZ
C
C  READ THE TERMOCOUPLE TEMPERATURES (DEGREES F)
      READ(5,250) TC3
      READ(5,250) TC6
C
C  READ THE TIME INCREMENT IN HOURS
      READ(5,400) DTIME
C
C  READ THE TOTAL TIME IN HOURS
      READ(5,400) TTIME
C
C READ AND WRITE THE DATA NUMBER
      READ(5,11) DATN
      WRITE(6,12) DATN
C
C  READ THE PARAMETERS FOR PRINTING DECISION
C  I.E. WHAT LENGTHS SHOULD BE PRINTED
      READ(5,902) NPRN
      DO 901 I=1,NPRN
         READ(5,902) IPRN(I)
  901 CONTINUE
C
C
  100 FORMAT(F7.1)
  200 FORMAT(I2)
  250 FORMAT(F10.5)
  300 FORMAT(I3)
  350 FORMAT(E20.5)
  400 FORMAT(F8.1)
  902 FORMAT(I3)
   11 FORMAT(A4)
   12 FORMAT(1H0,'THIS IS DATA NUMBER ',A4)
C
      RETURN
      END
C
C
      SUBROUTINE NEWINT(T,V,R,N,DZ,RAD,DR,AREA,TAVG,
     1  TB,TINIT,KFIRST,TB1,TB2,Q,Q1,NSEG,Z,
     2  COKETK,DTIME,FILMT,KTFLG,TC3,TC6,TIME)
```

```
C
C
C  THIS ROUTINE IS SIMILIAR TO 'INIT' HOWEVER
C  THIS ROUTINE DOES NOT CALL READER AND THIS ROUTINE
C  IS RESPONSIBLE FOR CALCULATING THE AMOUNT OF COKE
C  WHICH HAS BEEN DEPOSITED.  IT ALSO CALCULATES
C  THE NEW INSIDE RADIUS OF FLOW
C  THE ROUTINE ALSO CALCULATES THE AVERAGE FILM TEMPERATURE
C  FOR ONE COMPLETE TIME SEGMENT
C
      DIMENSION T(2,50),V(2,50),R(50)
      DIMENSION FILMT(100)
C
      KTFLG=0
      KFIRST=0
      Z=0.0
C
C  SET THE VELOCITY MATRIX TO ZERO
      DO 75 I=1,50
        V(1,I)=0.0
        V(2,I)=0.0
 75   CONTINUE
C
C  CALCULATE THE AVERAGE FILM TEMPERATURE AVGFT
C
      ADD=0.0
      DO 200 I=1,NSEG
      ADD=ADD+FILMT(I)
 200  CONTINUE
      AVGFT=ADD/NSEG
C
C
C  THIS IS THE SECTION WHICH DETERMINES THE COKE LAYER
C  THICKNESS IN INCHES.  SEE TEXT FOR DERIVATION OF EQUATION
C
      TK=(3483.68*EXP(-22727.74/(AVGFT+460)))
C
C  MUST INCLUDE TIME WHEN CONSIDERING COKE THICKNESS
C
      TMP=TIME-DTIME
      WRITE(6,991) TMP
 991  FORMAT(1H0,'*******************************************
'/
     1  1H0,' THE ENTIRE LENGTH FOR TIME ',F6.1,' HOURS HAS
',
     2  'BEEN COMPLETED')
      COKETK=TK*DTIME/12.+COKETK
C
      WRITE(6,992) AVGFT,TIME,COKETK
 992  FORMAT(1H0,'THE AVERAGE FILM TEMPERATURE FOR THE LENGT
H IS ',
     1  F9.2,' DEGREES F'/1X,'THE COKE THICKNESS BASED ON',
     2  'THIS TEMPERATURE AT TIME ',F6.1,' IS ',
     3  E14.5,' FT',1H1)
```

```
C  CALCULATE THE NEW VALUE FOR THE RADIUS
      RAD=RAD-(TK*DTIME/12.)
      DO 300 I=1,50
      T(1,I)=TINIT
      T(2,I)=0.0
 300  CONTINUE
C
C CALCULATE THE AREA AND FLOW RATE
      AREA=3.14159*RAD*RAD
      Q=Q1*AREA
      TAVG=TINIT
      TB1=TINIT
      TB2=TB1
C
      RETURN
      END
C
C
C
      SUBROUTINE PHYP(TAVG,API,AREA,Q,AK,RHO,CP,AVGV,
     1  HFLUX,FLUX,DZ,N,R,VIS,TB,RENN,RAD,THICK,TAUO)
C
C  THIS SUBROUTINE CALCULATES THE PHYSICAL PROPERTIES
C  OF CRUDE OIL (DENSITY, THERMAL CONDUCTIVITY, HEAT CAPACIT
Y)
C  EQUATIONS FOR DENSITY THERMAL CONDUCTIVITY AND
C  HEAT CAPACITY ARE FROM DATA GIVEN IN NELSON, W.L.
C  PETROLEUM REFINERY ENGINEERING, MCGRAW-HILL, 4TH ED. 1959
C
C
C  THIS ROUTINE ALSO CALCULATES THE AVERAGE VELOCITY
C  USING A MASS BALANCE
C  THE REYNOLDS NUMBER
C  AND THE THICKNESS OF THE LAMINAR SUBLAYER
C  IT THEN DETERMINES THE RADIAL PROFILE
C
      DIMENSION R(50)
C
C     CALCULATE THE DENSITY
      SG=.99864+1.56152E-03*API-3.278E-04*API*API
     1  -1.5195E-04*TAVG-1.342E-07*TAVG*TAVG
      RHO=SG*62.3
C
C
C
C     THERMAL CONDUCTIVITY
      AK = (6.48+(0.0455*API)-(0.00237*TAVG))/360000.
C
C     ** HEAT CAPCITY **
      CP=3.34998E-1+(2.16414E-3*API)+(5.86636E-4*TAVG)
C
C  CALCULATE THE NEW AVERAGE VELOCITY BASED UPON
C  THE ADJUSTED VALUE OF THE DENSITY
C
```

```
C  IT IS THE EQUATION OF CONTINUTITY
      AVGV=Q/RHO/AREA
C
C
C     CALCULATES THE REYNOLDS NUMBER
C
      VIS=VISC(API,TB,TAVG,RHO)
      RENN=RAD*2.*AVGV*RHO/VIS
C
C  FF IS THE FANNING FRICTION FACTOR
C  THE FRICTION FACTOR IS CALCULATED BY THE ROUND EQUATION
C
      FF=(((1.8*ALOG(RENN/(1.35*RENN*(1.5E-04/2./RAD)+6.5)))
**(-2.))/4.)
C
C  CALCULATE THE THICKNESS OF THE LAMINAR SUBLAYER
C
      TAUO=FF*RHO/2.*AVGV*AVGV
      THICK=5.*VIS/(SQRT(RHO*TAUO))
      THICK=THICK/2.
C
C  CALCULATE THE RADIAL PROFILE
C
C  NF IS THE NUMBER OF RADIAL SEGMENTS AFTER
C  THE FIRST RADIAL SEGMENT
      NF=N-1
      R(1)=RAD-THICK
      R2=R(1)/FLOAT(NF)
        DO 200 I=2,NF
        IM=I-1
        R(I)=R(IM)-R2
  200 CONTINUE
      R(N)=0.0
      NP=N+1
      NRM=N-1
      R(NP)=R(NRM)
      RETURN
      END
C
C
      FUNCTION VISC(API,TBB,TAVG,RHO)
C
C  THIS FUNCTION CALCULATES THE VISCOSITY FOR THE
C  CRUDE OIL
C
C  THE EQUATIONS ARE FROM AMIN, M.B., AND MADDOX, R.N.,
C  HYDROCARBON PROCESSING, VOL59, N12 DEC1980, P131-135
C
C  THIS FUNCTION IS USED BY SUBROUTINE PHYP
C
      T=TAVG
      TB=TBB
C     CONVERT T FROM F TO K
      T=273.15+((5./9.)*(T-32.))
```

```
      TB=273.15+((5./9.)*(TB-32.))
C
C  CONVERT T FROM F TO R
      TBR=TBB+459.67
C
C    CALCULATE SPECIFIC GRAVITY AT 60 DEGREES F (S)
      S=141.5/(API+131.5)
C
C  CALCUALTE THE CHARACTERIZATION FACTOR
      C=(TBR**(1./3.))/S
C
C  CLACULATE THER TERMS IN THE VISCOSITY EQUATION
      B=EXP(4.717+(0.00526*TB))
      A=(91.836*(TB**(-0.175))-29.263)*(C/B)
C
C  CALCUALTE THE VISCOSITY IN CENTISTOKES
      ANU=A*EXP(B/T)
C
C  CONVERT TO LBM/FT S
      VISC=ANU*RHO*10.764E-6
C
C
      RETURN
      END
C
C
C
      SUBROUTINE WALLT(TW1,TW2,T,Z,DZ,TC3,TC6,TWAVG)
      DIMENSION T(2,50)
C
C  IF THE WALL TEMPERATURE VARIES YOU NEED THIS
C  SUBROUTINE TO CALCULATE THE WALL TEMPERATURE AT
C  VARIOUS POINTS IN THE PIPE
C  THIS VERSION OF THE ROUTINE USES TWO WALL TEMPERATURES
C  ONE TEMPERATURE AT 3 FT AND ONE AT 6 FT
C  IT THEN FITS THESE TWO POINTS TO A LINE
C  AND THE TEMPERATURE AT ANY OTHER POINT IS ASSUMED
C  TO BE REPRESENTED BY THIS LINEAR FUNCTION
C
C
C
C  SET UP THE WALL TEMPERATURES
      SLOP=(TC6-TC3)/3.
      B=TC3-SLOP*3.
C
C
      TW1=B+SLOP*(Z-DZ)
      TW2=B+SLOP*Z
C
C  CALCULATE THE AVERAGE WALL TEMP FOR THIS INCREMENT
      TWAVG=(TW1+TW2)/2.
C
C  FIRST GUESS
      T(2,1)=B+SLOP*Z-.1
```

```
C
      RETURN
      END
C
C
C
      SUBROUTINE RENVL(VIS,AVGV,RAD,RHO,RENN
     1   ,V,R,N,KFIRST,DR,DZ,KTFLG,Y,TAUO)
C
C  THIS SUBROUTINE IS CALLED BY THE MAIN PROGRAM
C  THIS ROUTINE IS A DECISION ROUTINE
C  IT CALLS THE APPROPRIATE VELOCITY CALCULATION ROUTINE
C  DEPENDING UPON THE VALUE OF THE REYNOLDS NUMBER
C
C
      DIMENSION V(2,50), R(50),Y(50)
C
C
C  NOW CHECK THE REYNOLDS NUMBER AND USE THE
C  APPROPRIATE SUBROUTINE TO CALCULATE THE VELOCITY
C
C  LAMINAR FLOW
      IF (RENN.GT.2000.) GO TO 300
C
C *** LAMAR IS A SUBROUTINE WHICH DETERMINES
C     THE VELOCITY PROFILE FOR LAMINAR FLOW
C
         CALL LAMAR(V,AVGV,R,RAD,N)
      RETURN
C
C  TRANSITION REGION
  300 IF (RENN.GT.4000.) GO TO 400
C *** TRANS IS A SUBROUTINE WHICH CALCULATES THE
C     VELOCITY PROFILE IN THE TRANSITION REGION
C     BY USING A WEIGHTED AVERAGE (WEIGHED BY THE
C     VALUE OF THE REYNOLDS NUMBER) BASED ON A LAMINAR
C     FLOW PROFILE AND A TURBULENT FLOW PROFILE
C
           CALL TRANS(V,R,RAD,AVGV,N,RENN,KFIRST,
     1 DR,DZ,VIS,KTFLG,RHO)
      RETURN
C
C  IF THE VELOCITY HAS NOT BEEN ALREADY CALCULATED IT IS
C  TURBULENT
C
C  FIRST SET THE TURBULENT FLAG KTFLG
  400    KTFLG=1
C
C *** TURB IS A SUBROUTINE WHICH CALCULATES THE
C     VELOCITY PROFILE FOR TURBULENT FLOW
C     IT ALSO CALCULATES THE CORRECT PRESSURE DROP
C     FOR THE FLOW RATE SPECIFIED
C
      CALL TURB(V,R,RAD,RHO,DZ,VIS,N,DR,AVGV,
```

```
     1 KFIRST,KTFLG,Y,RENN,TAUO)
      RETURN
      END
C
C
C
      SUBROUTINE LAMAR (V,AVGV,R,RAD,N)
C
C     CALCULATE THE VELOCITY PROFILE FOR LAMINAR FLOW
      DIMENSION V(2,50),R(50)
C
C
C   CALCULATE NEW VALUE OF V
      DO 100 I=1,N
      V(2,I) = 2.*AVGV*(1.-(R(I)/RAD)**2.)
 100  CONTINUE
      RETURN
      END
C
C
C
C
      SUBROUTINE TURB(V,R,RAD,RHO,DZ,VIS,N,
     1 DR,AVGV,KFIRST,KTFLG,Y,RENN,TAUO)
C
C  THIS ROUTINE TAKES.THE AVERAGE VELOCITY AND SOLVES
C  FOR THE PROPER PRESSURE AND HENCE THE TURBULENT
C  VELOCITY PROFILE
C
C  THIS ROUTINE IS CALLED BY
C  1) SUBROUTINE RENVL
C  2) SUBROUTINE TRANS
C
      DIMENSION V(2,50), R(50),Y(50)
C
C
C  ETA IS THE VELOCITY CORRECTION FACTOR
C  MAKE TWO INITIAL GUESSES TO ETA FOR THE
C  SECANT METHOD
      ETAG1=1.0
      ETAG2=1.4
C
C  SET THE TOLERANCE TO BE USED BY THE SECN METHOD
C  AND THE FLAG USED BY THE SECANT ROUTINE
      ATOL=1.E-02
      IFLG=0
C
C  CALCULATE THE VELOCTIY PROFILE USING THE GUESSES
C
C *** VPP IS A SUBROUTINE WHICH CALCULATES THE
C     TURBULENT FLOW VELOCITY PROFILE
C *** TVAVG IS A SUBROUTINE WHICH CALCULATES THE
C     AVERAGE VELOCITY FOR THE TURBULENT FLOW PROFILE
C
```

```
 100  CALL VPP(R,V,ETAG1,RAD,RHO,DZ,VIS,N,Y,RENN,
     1  TAUO,AVGV,KFIRST)
      CALL TVAVG(V,N,R,DR,AVGV1,RAD)
C
      CALL VPP(R,V,ETAG2,RAD,RHO,DZ,VIS,N,Y,RENN,
     1  TAUO,AVGV,KFIRST)
      CALL TVAVG(V,N,R,DR,AVGV2,RAD)
C
C
C  THE SECANT ROUTINE NEEDS THE FUNCTION IN TERMS
C  OF F(X)=0
C
      F1=AVGV-AVGV1
      F2=AVGV-AVGV2
C
      CALL SECAN (ETAG1,ETAG2,X3,F1,F2,ATOL,IFLG)
      IF(IFLG.EQ.1) GO TO 200
C
C  TRY AGAIN
      ETAG1=ETAG2
      ETAG2=X3
      GO TO 100
 200  ETA=X3
      CALL VPP(R,V,ETA,RAD,RHO,DZ,VIS,N,Y,RENN,
     1  TAUO,AVGV,KFIRST)
C
      WRITE(6,43)ETA
 43   FORMAT(1H0,'ETA IS ',E11.4)
      CALL TVAVG(V,N,R,DR,AVGV,RAD)
      RETURN
      END
C
C
      SUBROUTINE VPP(R,V,ETA,RAD,RHO,DZ,VIS,N,Y,RENN,
     1  TAUO,AVGV,KFIRST)
C  THIS SUBROUTINE EVALUATES THE VELOCITY PROFILE FOR
C  TURBULENT FLOW
C
C  THIS ROUTINE IS CALLED BY SUBROUTINE TURB
C
      DIMENSION V(2,50),R(50),Y(50)
C
C
      FF=(((1.8*ALOG(RENN/(1.35*RENN*(1.5E-04/2./RAD)+6.5)))
**(-2.))/4.)
      VA=AVGV*SQRT(FF/2.)
C
C  CALCULATE SP
      DO 100 I=1,N
      S=RAD-R(I)
C  CALCULATE SP AND PUT IN AN ARRAY TO BE USED LATER
C  IN THE EDDY EQUATION
      SP=S*VA*RHO/VIS
      Y(I)=SP
```

```
 100  CONTINUE
C
C  THE EQUATIONS USED BY THIS ROUTINE TO EVALUATE
C  THE VELOCITY PROFILE ARE FROM
C  GEANKOPLIS, C.J.; "TRANSPORT PROCESSES AND UNIT OPERATION
S,"
C  ALLYN AND BACON, BOSTON, MASS., P127, (1978)
C
      DO 200 I=1,N
      IF(Y(I).LE.5.0) V(2,I)=VA*Y(I)
      IF(Y(I).GT.5.0.AND.Y(I).LE.30.0)
     1  V(2,I)=VA*ETA*(5.0*ALOG(Y(I))-3.05)
      IF(Y(I).GT.30.0) V(2,I)=VA*ETA*(2.5*ALOG(Y(I))+5.5)
 200  CONTINUE
      IF(KFIRST.EQ.1) GO TO 300
      DO 400 I=1,N
       V(1,I)=V(2,I)
 400  CONTINUE
 300  CONTINUE
      RETURN
      END
C
C
C
C
C
C
      SUBROUTINE TVAVG(V,N,R,DR,AVGV,RAD)
C
C  THIS ROUTINE CALCULATES THE AVERAGE VELOCITY FOR THE
C  TURBULENT FLOW PRFILE
C
C  THIS ROUTINE IS CALLED BY
C  1) SUBROUTINE TURB
C  2) SUBROUTINE TRANS
C
      DIMENSION V(2,50),R(50),F(50)
C  THERE ARE N+2 TERMS BECAUSE THE WALL AND THE
C  CENTER VALUES OF F ARE ZERO
      N2=N+2
      DO 100 I=1,N
        F(I+1)=V(2,I)*R(I)
 100  CONTINUE
      F(1)=0.0
      F(N2)=0.0
      CALL TRAP(N2,R,F,RESULT,RAD)
      ANUM=RESULT
      DO 200 I=1,N
        F(I)=R(I)
 200  CONTINUE
      F(1)=0.0
      F(N2)=0.0
      CALL TRAP(N2,R,F,RESULT,RAD)
      AVGV=ANUM/RESULT
```

```
      RETURN
      END
C
C
      SUBROUTINE TRAP(N,R,F,ATRAP,RAD)
      DIMENSION R(50),F(50)
C
C  THIS SUBROUTINE PERFORMES THE TRAPAZOIDAL RULE
C   FOR THE INTEGRAL OF F DX
C  THIS ROUTINE IS CALLED BY:
C  1) SUBROUTINE BULKT
C  2) SUBROUTINE TVAVG
C
C
      ATRAP=((F(1)+F(2))*(RAD-R(1))/2.0)
      NM=N-1
      DO 100 I=2,NM
         IP=I+1
      IM=I-1
C
      TERM=((F(I)+F(IP))*(R(IM)-R(I))/2.0)
      ATRAP=ATRAP+TERM
  100 CONTINUE
      RETURN
      END
C
C
C
C
C
C
C
      SUBROUTINE SECAN(X1,X2,X3,F1,F2,ATOL,IFLG)
C
C  PERFORMS SECANT ITERATION WHERE X3 IS THE NEXT GUESS
C  IF THE TOLERANCE IS MET THE FLAG (IFLG) IS SET TO 1
C  THIS ROUTINE IS CALLED BY SUBROUTINE TURB
C
C  SAFETY IN CASE F1-F2=0
      IF (F1.NE.F2) GO TO 100
      IFLG=1
      RETURN
  100 X3=X2-(F2/((F2-F1)/(X2-X1)))
C  IF X3 AND X2 DIFFER BY LESS THAN THE SPECIFICED
C  TOLERENCE (ATOL) SET THE FLAG (IFLG) TO 1
      IF (ABS(X3-X2).LE.ATOL) IFLG=1
      X4=X3-X2
      RETURN
      END
C
C
C
C
      SUBROUTINE TEMP (T,V,DZ,DR,CP,RHO,AK,R,N,FLUX
```

```
     1,KTFLG,Y,ED,Z,TW1,TW2,RAD)
      DIMENSION T(2,50),V(2,50),R(50),ED(50)
      DIMENSION Y(50)
C
C  CALCULATE THE WALL TEMPERATURE BASED ON THE DISTANCE
C  DOWNSTREAM
C
C
C  CALCULATE THE EDDY DIFFUSIVITY IF LAMINAR FLOW
C  THE EDDY SUBROUTINE WILL MAKE THE ED ARRAY ZERO
      CALL EDDY(T,V,R,ED,N,KTFLG,Y,RAD)
C
C
C
C  CALCULATE THE TEMP PROFILE BY THE CRANK NICOLSON
C  METHOD CALL THE TCRANK SUBROUTINE
C
C *** TCRANK IS A SUBROUTINE WHICH DETERMINES
C     THE TEMPERATURE PROFILE USING THE CRANK
C     NICKOLSON METHOD TO SOLVE THE PDE'S
C
      CALL TCRANK(T,V,R,AK,RHO,CP,ED,N,DZ)
      RETURN
      END
C
C
C
C
      SUBROUTINE TCRANK(T,V,R,AK,RHO,CP,ED,N,DZ)
C  THIS ROUTINE CALCULATES THE TEMPERATURE PROFILE BY
C  FOR TURBULENT FLOW
C
C  FOR A THROUGH DESCRIPTION OF THIS ROUTINE PLEASE SEE
C  THE TEXT OF THE REPORT INCLUDED WITH THIS PROGRAM
C
C  THIS ROUTINE SOLVES A PARTIAL DIFFERENTIAL EQUATION
C  BY THE CRANK NICOLSON METHOD
C
      DIMENSION TR1(50),TR3(50),TR2(50),D(50)
      DIMENSION T(2,50),V(2,50),R(50),AN(50)
      DIMENSION AL(50),B(50),G(50),ED(50)
      DIMENSION E(50)
      NM=N-1
      NP=N+1
      ALPHA=AK/RHO/CP
C
C  CALCULATE THE B,G,D TERMS
      DO 100 I=2,NM
      IM=I-1
      IP=I+1
      DR=R(IM)-R(I)
      B(I)=DZ/DR/4./V(2,I)/R(I)*(ALPHA+ED(I))
      G(I)=DZ/2./DR/DR/V(2,I)*(ALPHA+ED(I))
      DEDR=(ED(IP)-ED(I-1))/2./DR
```

```
      E(I)=DZ/4./DR/V(2,I)*DEDR
100   CONTINUE.
C
C  CALCULATE TERMS FOR THE CENTER
      G(N)=DZ/1./DR/DR/V(2,N)*(ALPHA+ED(N))
C
C  SET THE TRIDIAGONAL MATRIX TO ZERO
      DO 200 I=1,NM
      TR1(I)=0.0
      TR2(I)=0.0
      TR3(I)=0.0
      D(I)=0.0
200   CONTINUE
C
C  TERMS FOR THE FIRST EQUATION
      TR2(1)=(-1.)*(2.*G(2)+1)
      TR3(1)=G(2)+B(2)+E(2)
      D(1)=-T(2,1)*(G(2)-B(2)-E(2))-T(1,3)*(B(2)+G(2)+E(2))-
     1  T(1,2)*(1-2.*G(2))-T(1,1)*(G(2)-B(2)-E(2))
C
C  LAST EQUATION
      NM2=N-2
      TR1(NM)=2.*G(N)
      TR2(NM)=(-1.)*(1.+2.*G(N))
      D(NM)=-1.*T(1,N)*(-2.*G(N)+1.)-2.*T(1,NM)*G(N)
C
C  ALL OTHER EQUATIONS
      DO 250 I=3,NM
      IM=I-1
      IP=I+1
      TR1(IM)=G(I)-E(I)-B(I)
      TR2(IM)=(-1.)*(2.*G(I)+1)
      TR3(IM)=B(I)+G(I)+E(I)
      D(IM)=-T(1,IP)*(B(I)+G(I)+E(I))-T(1,I)*(1.-2.*G(I))-
     1  T(1,IM)*(G(I)-E(I)-B(I))
250   CONTINUE
      IF=1
      CALL TRIDAG(IF,NM,TR1,TR2,TR3,D,AN)
C
C  SET SOLUTION VECTOR TO T(2,I)
      DO 900 I=2,N
      IM=I-1
      T(2,I)=AN(IM)
      IF(T(2,I).LT.T(1,I)) T(2,I)=T(1,I)
900   CONTINUE
C
C  SYMMETRY
      NP=N+1
      T(2,NP)=T(2,NM)
      RETURN
      END
C
C
C
```

```
      SUBROUTINE TRIDAG(IF,L,A,B,C,D,V)
      DIMENSION A(50),B(50),C(50),D(50),V(50),BETA(50)
      DIMENSION GAMMA(50)
C
C  COMPUTE INTERMEDIATE ARRAYS BETA AND GAMMA
      BETA(IF)=B(IF)
      GAMMA(IF)=D(IF)/BETA(IF)
      IFP1=IF+1
      DO 1 I=IFP1,L
       BETA(I)=B(I)-A(I)*C(I-1)/BETA(I-1)
    1 GAMMA(I)=(D(I)-A(I)*GAMMA(I-1))/BETA(I)
C
C  COMPUTE THE FINAL SOLUTION VECOTR V
      V(L)=GAMMA(L)
      LAST=L-IF
      DO 2 K=1,LAST
      I=L-K
    2 V(I)=GAMMA(I)-C(I)*V(I+1)/BETA(I)
      RETURN
      END
C
C
C
      SUBROUTINE BULKT(T,V,R,TB2,N,RAD)
C
C  THIS SUBROUTINE CALCULATES THE BULK TEMPERATURE
      DIMENSION T(2,50),V(2,50),R(50)
      DIMENSIONF(50)
C
C  F AT THE WALL AND THE CENTER IS ZERO
C  THERE ARE N+2 F TERMS
      N2=N+2
      N1=N+1
      DO 100 I=1,N
      F(I+1)=T(2,I)*V(2,I)*R(I)
  100 CONTINUE
      F(1)=0.0
      F(N2)=0.0
      CALL TRAP(N2,R,F,RESULT,RAD)
      ANUM=RESULT
      DO 200 I=1,N
      F(I+1)=V(2,I)*R(I)
  200 CONTINUE
      F(1)=0.0
      F(N2)=0.0
      CALL TRAP(N2,R,F,RESULT,RAD)
      TB2=ANUM/RESULT
      RETURN
      END
C
C
C
C
C
```

```
C
C
      SUBROUTINE PRN1(RAD,N,DR,DZ,API,TB,Q,TC3,TC6,
     1  DTIME,TTIME)
C
C  THIS ROUTINE PRINTS THE VALUES WHICH ARE CONSTANT
C  THROUGHTOUT THE LENGTH OF THE PIPE
C
C
C  THIS ROUTINE IS CALLED BY SUBROUTINE INIT
C
      WRITE(6,10)
      WRITE(6,20)
      WRITE(6,100) RAD,N,DZ
      WRITE(6,110) TC3,TC6
      WRITE(6,125) Q
      WRITE(6,200) API,TB
      WRITE(6,401) DTIME,TTIME
   10 FORMAT (1H1, '*****************************************
****'/
     1          1H0,'************* COKING  PROGRAM ***********
****'/
     2          1X, '*************        BY        ***********
****'/
     3          1X, '************* JOSEPH POLIMENI ***********
****'/
     4          1H0,'*****************************************
***')
   20 FORMAT(1H0'THE DATA FOR THIS SERIES IS AS FOLLOWS:')
  100 FORMAT(1H0,'THE PIPE RADIUS IS ',F9.5,' FEET'/
     1  1X,'THE NUMBER OF RADIAL SEGMENTS IS ',I2/1X,
     3  'THE LENGTH SEGMENT IS ',F9.5,'FEET')
  110 FORMAT(1X,'TEMP AT THERMOCOUPLE 3 IS ',F4.0,' F',
     1   '  TEMP AT THERMOCOUPLE 6 IS ',F4.0,' F')
  125 FORMAT(1X,'THE INITIAL FLOW RATE IS ',F10.5,' LBM/SEC'
)
  200 FORMAT (1H0,'THE OIL PROPERTIES: '/1X,
     1  'THE API GRAVITY IS ',F9.3/1X,
     2  'THE 50% BOILING TEMP. IS ',F9.3,' F')
  401 FORMAT(1H0,'THE INCREMENTAL TIME WILL BE ',F6.1,' HOUR
S'/
     1  1X,'THE TOTAL TIME WILL BE ',F6.1,' HOURS'/1H1)
C
        RETURN
        END
C
C
C
       SUBROUTINE PRN2(V,T,R,TB1,TB2,RHO,CP,AK,AVGV,
     1  RENN,Z,VIS,N,I,ED,Q,OLDT,DZ,RAD,THICK,TIME,
     2  QMCP,TSKIN,TW1,TW2)
C
C     PRINT THE VALUES WHICH CHANGE AT EACH LENGTH SEGMENT
C
```

```
C  THIS ROUTINE IS CALLED BY THE MAIN PROGRAM
C
        DIMENSION V(2,50),T(2,50),R(50)
       DIMENSION ED(50)
C
C
       O=0.0
C
       OZ=Z-DZ
       WRITE(6,75) TIME
       WRITE(6,100) OZ,Z
       WRITE(6,300)TB1
       WRITE(6,305) RHO,VIS,AK,CP
       WRITE(6,350) RENN
       WRITE(6,400) AVGV,TB2
       WRITE(6,450) TSKIN
C
       QA=QMCP*3600*1/DZ/(2.*3.14156*RAD)
       WRITE(6,600) QA
       WRITE(6,470)
       WRITE(6,490)
       WRITE(6,495) RAD,O,O,TW1,TW2,O
        NP=N+1
        DO 711 J=1,N
        WRITE(6,500) R(J),V(1,J),V(2,J),T(1,J),T(2,J),ED(J)
  711  CONTINUE
   75  FORMAT(1X,'*****************************************
*****'/
     1        1H0,'    THE PRESENT TIME IS ',F9.1,' HOURS'/
     2        1H0,'*****************************************
*****')
  100  FORMAT(1H0,'THE PAST LENGTH SEGMENT IS ',F9.5,' FEET'/
     1         1X,'THE PRESENT LENGTH SEGMENT IS ',F9.5,' FEE
T')
  300  FORMAT(1H0,'*****************************************
*****'/
     1          1X,'      THE PHYSICAL PROPERTIES ARE BASED O
N THE',
     2    ' BULK TEMPERATURE OF'/2X,'THE PAST LENGTH SEGMENT
 ',
     3    'WHICH IS ',F5.1,' F'/1H0)
  305  FORMAT(1X,'THE DENSITY IS ',F9.3,' LBM/FT3'/
     1       1X, 'THE VISCOSITY IS ',E12.5,' LBM/FT-S'/
     2       1X,'THE THERMAL CONDUCTIVITY IS ',E12.5,' BTU/S-
FT-F'/
     3       1X,'THE HEAT CAPACITY IS ',F9.5,'BTU/LBM-F')
  400  FORMAT(1H0,'*****************************************
*****'/
     1       1X,'THE AVERAGE VELOCITY FOR THE PRESENT LENGTH
IS ',
     2           E12.5,' FT/S'/
     4      1H0,'THE BULK TEMPERATURE FOR THE PRESENT LENGTH
IS ',
     5            F11.5,' DEGREES F')
```

```
  350  FORMAT(1H0,'***********************************************'/
     1       1H0,'THE REYNOLDS NUMBER IS ',F9.2)
  450  FORMAT(1H0,'THE OUTSIDE TUBE WALL TEMPERATURE IS ',
     1  E12.5,'DEGREES F')
  470  FORMAT(1H0,'***********************************************',
     5              '*************************************************'/
     1  1H0,3X,'RADIUS',12X,'VELOCITY',18X,'TEMPERATURE'
     2     ,7X,'EDDY DIFFUSIVITY'/
     3     1X,14X,'PREVIOUS',5X,'PRESENT',7X,'PREVIOUS',5X,
     4     'PRESENT',5X,'PRESENT')
  490  FORMAT(1X,4X,'FT',8X,' FT/S ',6X,' FT/S ',8X,
     1     'DEGREES F',4X,'DEGREES F',4X,'FT2/S')
  495   FORMAT(1H0,F10.7,2X,E10.4,2X,E10.4,6X,F9.4,3X,F9.4,
     1  3X,E10.4,' *** WALL ***')
  500   FORMAT(1X,F10.7,2X,E10.4,2X,E10.4,6X,F9.4,3X,F9.4,
     1  3X,E10.4)
  600  FORMAT(1X,'THE HEAT FLUX FOR THIS LENGTH SEGMENT IS ',E20.5,
     1   ' BTU/HR FT2')
C
C
       WRITE(6,991)
  991  FORMAT(1H0,'******************************************',
     1              '*******************************************'/1X,
     2              '*******************************************',
     3              '*******************************************'/1H1)
       RETURN
       END
C
C
C
C
C
C
C
C
       SUBROUTINE RESET (X,N)
C  THIS SUBROUTINE SET ANYTHING IN THE SECOND ROW TO
C  THE FIRST ROW IE  NEW VALUES OF VELOCITY OR
C  TEMPERATURE BECOMES OLD VALUES
C
C  THIS ROUTINE IS CALLED BY THE MAIN PROGRAM
C
       DIMENSION X(2,50)
       NP=N+1
       DO 100 I=1,NP
       X(1,I)=X(2,I)
```

```
  100   CONTINUE
        RETURN
        END
C
C
C
        SUBROUTINE TRANS(V,R,RAD,AVGV,N,RENN,KFIRST,
       1 DR,DZ,VIS,KTFLG,RHO)
C
C  THIS ROUTINE CALCULATES THE VELOCITY PROFILE IN THE
C  TRANSITION ZONE BY USING A WEIGHTED AVERAGE BETWEEN
C  REYNOLDS NUMBERS 2000-4000
C
C  THIS ROUTINE IS CALLED BY SUBROUTINE RENVL
C
        DIMENSION VLAM(2,50),VTURB(2,50),V(2,50)
        DIMENSION R(50)
C
C
C  FIRST CALCULATE THE LAMINAR FLOW PROFILE
        CALL LAMAR(V,AVGV,R,RAD,N)
        DO 20 IJ=1,N
           VLAM(2,IJ)=V(2,IJ)
 20     CONTINUE
        IF (KFIRST.EQ.1) GO TO 25
C
C  CALCULATE THE TURBULENT FLOW PROFILE
  25    CONTINUE
        CALL TURB(V,R,RAD,RHO,DZ,VIS,N,DR,AVGVT,
       1 KFIRST,KTFLG,Y,RENN,TAUO)
C
C  CALCULATE THE WEIGHTS
        LWT=2.-(RENN/2000.)
        TWT=(RENN/2000.)-1.
        NP=N+1
        DO 100 I=1,N
           V(2,I)=LWT*VLAM(2,I)+TWT*V(2,I)
  100   CONTINUE
C
C  CALCULATE THE AVERAGE VELOCITY
        CALL TVAVG(V,N,R,DR,AVGVT,RAD)
C
C  NORMALIZE TO FORCE PROFILE TO GIVE AVGV
        DO 200 I=1,NP
           V(2,I)=V(2,I)*AVGV/AVGVT
  200   CONTINUE
        RETURN
        END
C
C
        SUBROUTINE EDDY(T,V,R,ED,N,KTFLG,Y,RAD)
C
C  THIS ROUTINE DETERMINES THE EDDY DIFFUSIVITY FOR
C  EACH RADIAL SEGMENT
```

```
C
C  THIS ROUTINE IS CALLED BY SUBROUTINE TEMP
C
      DIMENSION T(2,50),V(2,50),R(50),ED(50)
      DIMENSION Y(50)
C
C  CHECK FOR TURBULENT FLOW
C  IF LAMINAR SET ED ARRAY TO ZERO AND RETURN
       IF(KTFLG.EQ.1) GO TO 20
      DO 10 I=1,200
        ED(I)=0.0
 10   CONTINUE
      RETURN
 20   CONTINUE
C
C  SET DIELSER CONSTANT
      DK=0.36
C
C  CALCULATE PRANDTLE MIXING LENGTH
      NM=N-1
      NP=N+1
      DO 100 I=1,NM
      IM=I-1
      IP=I+1
C
C  CALCULATE THE DISTANCE FROM THE WALL
      S=RAD-R(I)
C
C  CALCUALTE THE MIXING LENGTH
C
C  SAFETY SO EXP IS NOT EXCEEDED
      IF(Y(I).GT.50.) Y(I)=50.
      AL=DK*S*(1.-(1./EXP(Y(I)/26.)))
C
C  CALCULATE DV/DR
      DVDR=(V(2,IP)-V(2,I))/((R(I)-R(IP)))
      ED(I)=AL*AL*1*DVDR
C
C  INCLUDE A SAFETY FEATURE SO THAT
C  NEGATIVE EDDY DIFFUSIVITIES ARE AVOIDED
      IM=I-1
      IF(ED(I).LE.0.0) ED(I)=ED(IM)
 100  CONTINUE
      ED(N)=ED(NM)
      ED(NP)=ED(N)
      RETURN
      END
C
C
C
      SUBROUTINE QCALC(TB1,T,R,V,AVGV,AK,DZ,N,RHO
     1  ,QMCP,TB2,CP,RAD)
C
C THIS ROUTINE CALCULATES Q
```

```
C
C THIS ROUTINE IS CALLED BY THE MAIN PROGRAM
C
      DIMENSION T(2,50),R(50),V(2,50)
      CALL BULKT(T,V,R,TB2,N,RAD)
      DELT=TB2-TB1
C
      PI=3.14159
      QMCP=AVGV*PI*RHO*(R(1)**2.)*DELT*CP
      RETURN
      END
C
C
C
      SUBROUTINE TADJ(T,QMCP,DZ,AK,RAD,R,TW2)
C
C  THIS ROUTINE CALCULATES WHAT THE TEMPERATURE
C  NEXT TO THE WALL SHOULD BE BASED UPON THE
C  Q CALCULATED BY M*CP*DELTA T
C
C  THIS ROUTINE IS CALLED BY
C  MAIN PROGRAM
C
         DIMENSION T(2,50),R(50)
         TERM=2.*3.14159*DZ*AK*RAD
         T(2,1)=QMCP/TERM*(R(1)-RAD)+TW2
      RETURN
      END
C
C
      SUBROUTINE SKIN(QMCP,TWAVG,RAD,ROUT,RIN,TSKIN,DZ)
C
C
      COKEK=0.161
      STEELK=8.52+4.17E-03*TWAVG
      Q=QMCP*3600.
      TSKIN=Q*((1/COKEK)*ALOG(RIN/RAD)+(1/STEELK)*ALOG(ROUT/RIN))
     1  /2./3.14159/DZ+TWAVG
      RETURN
      END
C
C
C
C
C
C
C
C
C
C
C
C
C *** VARIABLE DICTIONARY FOR ENTIRE PROGRAM ***
```

```
C
C      A-INITIAL LIMIT OF INTEGRATION
C    ADD-SUM OF ALL FILM TEMPERATURES FOR A PARTICULAR
C          TIME SEGMENT.
C     AK-THERMAL CONDUCTIVITY OF CRUDE OIL
C     AL-PRANDTLE MIXING LENGTH
C    API-API GRAVITY
C   AREA-AREA OF FLOW
C   ATOL-TOLERENCE FOR SECANT METHOD
C  AVGFT-AVERAGE OF ALL FILM TEMPERATURES FOR A PARTICULAR
C          TIME SEGMENT
C   AVGV-AVERAGE VELOCITY
C   BTOL-TOLERENCE FOR TEMPERATURE NEXT TO WALL
C
C      C-CHARACTERIZATION FACTOR
C  CHECK-THE ABSOLUTE VALUE OF THE DIFFERENCE BETWEEN
C          THE LAST VALUE OF THE TEMPERATURE NEXT TO THE
C          WALL AND THE CURRENT VALUE OF THE TEMPERATURE
C          NEXT TO THE WALL
C COKETK-COKE THICKNESS
C     CP-HEAT CAPACITY OF THE CRUDE OIL
C   DATN-NAME OF DATA SET
C   DELT-DIFFERENCE BETWEEN PRESENT BULK TEMPERATURE AND
C           PAST LENGTH BULK TEMPERATURE
C  DTIME-TIME INCREMENT
C  DVDR-FORWARD DIFFERENCE APPROXIMATION TO THE PARTIAL
C         DERIVATIVE OF VELOCITY WITH RESPECT TO R
C     DZ-LENGTH INCREMENT
C    ETA-CORRECTION FACTOR FOR VELOCITY PROFILE
C  ETAG1-FIRST GUESS OF ETA -- USED BY SECANT METHOD
C  ETAG2-SECOND GUESS OF ETA -- USED BY SECANT METHOD
C     F1-VALUE OF F(ETAG1) USED BY SECANT METHOD
C     F2-VALUE OF F(ETAG2) USED BY SECANT METHOD
C     FF-FANNING FRICTION FACTOR
C  FILMT-ARRAY WHICH CONTAINS THE VALUE OF THE
C          TEMPERATURE NEXT TO THE WALL FOR EACH
C          LENGTH SEGMENT
C  IFLG-FLAG, INDICATES WHETHER THE SECANT METHOD HAS
C         CONVERGED OR NOT: 0 MEANS NOT CONVERGED YET,
C         1 INDICATES THAT IT HAS CONVERGED
C    IP-PRINTER VARIABLE, USED TO INDICATE IF ALL THE
C         VALUES PERTAINING TO A PARTICULAR TIME SEGMENT SHOUL
D
C         BE PRINTED.
C  IPRN-PRINTER ARRAY, CONTAINS WHICH PARTICULAR TIME SEGMEN
TS
C         WILL HAVE ALL THE VALUES PERTAINING TO IT PRINTED
CKFIRST-FLAG, 0 INDICATES FIRST TIME THROUGH, 1 INDICATES
C         IT HAS ALREADY BEEN THROUGH THE ENTIRE LENGTH ONCE.
C KTFLG-FLAG, WHICH INDICATES LAMINAR OR TURBULENT FLOW
C         0 INDICATES LAMINAR, 1 INDICATES TURBULENT
C   LWT-A WEIGHT FACTOR USED WHEN IN TRANSITION REGION
C         A LINEAR FUNCTION OF REYNOLDS NUMBER, THIS
C         VARIABLE GIVES THE WEIGHT TO THE LAMINAR PROFILE
```

```
C    NF-NUMBER OF RADIAL SEGMENTS
C    NP-N+1
C  NPRN-PRINTER VARIABLE, USED TO INDICATE THE TOTAL AMOUNT OF
C        TIME SEGMENTS WHICH WILL HAVE ALL THE VALUES PERTAINING
C        TO IT PRINTED
C   NRM-N-1
C  NSEG-NUMBER OF LENGTH SEGMENTS IN ONE TIME PERIOD
C     Q-FLOW RATE IN LBM/FT2-SEC
C    Q1-FLOW RATE IN LBM/S
C  QMCP-HEAT FLUX CALCULATED BY M*CP*DELTA T
C    R2-SIZE OF RADIAL SEGMENT
C   RAD-INSIDE RADIUS OF FLOW (IF THERE IS NOT COKE
C        THIS IS THE INSIDE RADIUS OF THE TUBE)
C  RENN-REYNOLDS NUMBER
C   RHO-DENSITY OF THE CRUDE OIL (PRESENT LENGTH SEGMENT)
C  ROUT-OUTSIDE TUBE RADIUS
C    SG-SPECIFIC GRAVITY OF CRUDE OIL
C  TAU0-SHEAR STRESS AT THE WALL OF THE TUBE
C   TB1-BULK TEMPERATURE AT PREVIOUS LENGTH INCREMENT
C   TB2-BULK TEMPERATURE AT CURRENT LENGTH INCREMENT
C   TC3-TEMPERATURE AT THERMOCOUPLE NUMBER 3
C   TC6-TEMPERATURE AT THERMOUCOUPLE NUMBER 6
C    TH-HOLDS THE VALUE OF T NEXT TO THE WALL
C THICK-ONE HALF OF THE THICKNESS OF THE LAMINAR SUBLAYER
C  TIME-CURRENT TIME
C TINIT-INITIAL TEMPERATURE (BULK TEMPERATURE OF CRUDE OIL
C        INTO TUBE)
C    TK-AMOUNT OF COKE DEPOSITED FOR ONE TIME SEGMENT.
C TTIME-FINAL TIME
C    TB-FIFTY PERCENT BOLING POINT
C   TB1-BULK TEMPERATURE AT PREVIOUS LENGTH INCREMENT
C   TB2-BULK TEMPERATURE AT CURRENT LENGTH INCREMENT
C    TH-HOLDS THE VALUE OF T NEXT TO THE WALL
C   TW1-TEMPERATURE AT FLUID SOLID (TUBE WALL OR COKE LAYER)
C        INTERFACE AT PREVIOUS LENGTH SEMGMENT
C   TW2-TEMPERATURE AT FLUID SOLID INTERFACE AT PRESENT LENGTH
C        SEGMENT
C TWAVG-AVERAGE TEMPERATURE AT FLUID SOLID INTERFACE
C        (AVERAGE BASED ON PAST LENGTH SEGMENT AND PRESENT
C        LENGTH SEGMENT)
C   TWT-A WEIGHT FACTOR USED WHEN IN TRANSITION REGION
C        A LINEAR FUNCTION OF REYNOLDS NUMBER USED TO
C        DETERMINE HOW MUCH OF THE VELOCITY PROFILE
C        IS TURBULENT
C
C     V-ARRAY CONTAINING THE VELOCITY PROFILE:
C        V(1,X) CONTAINS THE PAST LENGTH SEGMENT VELOCITY PROFILE
C        V(2,X) CONTAINS THE CURRENT LENGTH SEGMENT VELOCITY
C        PROFILE
C    VA-DIMENSIONLESS VELOCITY
```

```
C   VIS-VISCOSITY OF CRUDE OIL
C  VLAM-ARRAY USED TO CONTAIN THE LAMINAR FLOW VELOCITY
C       PROFILE.
C       PROFILE
C     Z-LENGTH
```

APPENDIX B

INPUT FORMAT FOR PROGRAM

HOW TO USE THE PROGRAM

You will need to know the following

1. The wall temperature for the entire length of the tube (or make a linear assumption as described below).

2. The initial crude oil temperature.

3. The flow rate.

4. The inside and outside radius of the tube.

5. The API gravity and mid boiling point of the crude oil

THE WALL TEMPERATURE

Subroutine WALLT determines the wall temperature at a particular length. In its present form, the subroutine takes the wall temperature at 3 and 6 feet downstream, and uses the two values to assume a linear profile for the entire length of the tube. If the temperature profile is different from this the user must change the way TW1 and TW2 are calculated (TW1 is the tube wall temperature at the past axial segment, TW2 is the tube wall temperature at the present axial segment). For example:

The lines to be changed in subroutine WALLT are:

```
SLOP = (TC6 - TC3)/3.
   B = TC3 - SLOP*3.
 TW1 = B + SLOP * (Z-DZ)
 TW2 = B + SLOP * Z
```

say we know the wall temperature at 2 and 7 feet downstream and we still want a linear profile. Then TC6 would represent the temperature at 7 feet, and TC3 would represent the temperature at 3 feet. The first two lines would be changed to the following:

```
SLOP = (TC6 - TC3)/5.
   B = TC3 - SLOP*5
```

DATA ENTRY FORMAT

The data is entered with cards or a data file.

CARD 1

The initial bulk temperature in F

The format for this card is F7.1

```
example:  column  1  2  3  4  5  6  7
                  6  4  0  .  0
```

would indicate that the initial bulk temperature is 640 F.

CARD 2

The flow rate in lbm/ft2-s

The format for this card is F7.1

```
example:  column  1  2  3  4  5  6  7
                  1  4  3  .  0
```

would indicate that the flow rate is 143 lbm/ft2-s.

CARD 3

* A Value The User Chooses *

The number of radial segments

The format for this card is I2

```
example:  column  1  2
                  4  0
```

would indicate 40 radial segments

CARD 4

Inside radius of tube in inches

The format for this card is F10.5

```
example:   column   1  2  3
                    0  .  3
```

would indicate 0.3 inches

CARD 5

API gravity of the crude oil

The format for this card is F10.5

```
example:   column   1  2  3  4
                    2  9  .  6
```

would indicate an API gravity of 29.6

CARD 6

Mid-point boiling temperature of crude oil in F.

The format for this card is F10.5

```
example:   column   1  2  3  4  5
                    7  0  1  .  0
```

would indicate a mid-point boiling temperature of 701 F.

CARD 7

Outside radius of tube in inches.

The format for this card is F10.5

```
example:   column   1  2  3
                    0  .  5
```

would indicate an outside tube wall radius of 0.5 inches.

CARD 8

* A Value the User Chooses *

The number of axial segments

The format for this card is I3

```
example:  column  1  2  3
                     1  8
```

would indicate 18 axial segments

CARD 9

The value of z in feet.

The format for this card is E20.5

```
example:  column  1  2  3
                  0  .  5
```

would indicate that each axial increment is 0.5 feet.

CARD 10

The temperature of the tube wall three feet downstream in F

The format for this card is F10.5

```
example:  column  1  2  3  4  5
                  8  2  0  .  0
```

would indicate that the temperature of the tube wall three feet downstream is 820 F.

CARD 11

The temperature of the tube wall six feet downstream in F

The format for this card is F10.5

```
example:  column  1  2  3  4  5
                  8  3  0  .  0
```

would indicate that the temperature of the tube wall six feet downstream is 830 F.

CARD 12

* A User Chosen Value *

The time increment in hours.

The format for this card is F8.1

```
example:  column  1  2  3  4
                  9  3  .  0
```

would indicate that the time increment is 93 hours.

CARD 13

The total time in hours.

The format for this card is F8.1

```
example:  column  1  2  3  4
                  9  3  .  0
```

would indicate that the total time is 93 hours.

CARD 14

The data number. This is only a name to give to the data. This is useful when running many data sets at one time.

The format for this card is A4

```
example:  column 1  2  3  4
                 D  4
```

would indicate that the name of this series is D4.

CARDS USED TO CONTROL PRINTING

The program prints the results with routine PRN2. Array IPRN and variable NPRN are used to limit the computer printout. The results for each axial segment for the entire tube length will be printed, but only at the time increments specified. For example: If the total time of the test is 200 hours, and you want the coke to be layered at 100 and at 200 hours. There are three time segments (initial, 100 and 200 hours), but say only the value for the initial time and at 200 hours are desired. NPRN has the number of time increments to be printed, in this case NPRN is two. Array IPRN will have 2 values which correspond to the desired time increment. In this case IPRN(1) would equal zero (for the initial time segment) and IPRN(2) would equal two (for the value at 200 hours).

CARD 15

The value of NPRN (the number of entire length segments to print).

The format for this card is I3

```
example:  column  1  2  3
                        2
```

would indicate that the results for two time increments will be printed.

CARD 16 ETC.

The number of cards here will depend upon the value of CARD 15. If the value on CARD 15 is one, then only one card will follow CARD 15. Assume that CARD 15 has the value two on it, we will need two more cards after CARD 15.

The time increment to print the results for.

Format for this card is I3

```
example:  column  1  2  3
                        0
```

indicates that the initial time segment results should be printed.

CARD 17

The time increment to print the results for.

Format for this card is I3

```
example:  column  1  2  3
                        1
```

indicates that the second time segment results should be printed.

APPENDIX C

SAMPLE PRINTOUT FROM PROGRAM

```
THIS IS DATA NUMBER  04

**********************************************
************ COMING  PROGRAM ****************
************        BY        ***************
************** JOSEPH POLIMENI ***************
**********************************************

THE DATA FOR THIS SERIES IS AS FOLLOWS:

THE PIPE RADIUS IS    0.02500 FEET
THE NUMBER OF RADIAL SEGMENTS IS 41
THE LENGTH SEGMENT IS    0.50001 FEET
TEMP AT THERMOCOUPLE 3 IS 820. F  TEMP AT THERMOCOUPLE 6 IS 830. F
THE INITIAL FLOW RATE IS     0.28078 LBM/SEC

THE OIL PROPERTIES:
THE API GRAVITY IS     29.600
THE 50% BOILING TEMP. IS    701.000 F

THE INCREMENTAL TIME WILL BE  191.0 HOURS
THE TOTAL TIME WILL BE   191.0 HOURS
```

NORMALLY THE PROGRAM PRINTS THE RESULTS FOR EACH AXIAL SEGMENT. IN ORDER TO CONSERVE SPACE, ONLY THE RESULTS FROM 0.5, 1.0, 4.5, AND 9.0 FEET WITH AND WITHOUT COKE HAVE BEEN INCLUDED.

****

THE PRESENT TIME IS 0.0 HOURS

****

THE PAST LENGTH SEGMENT IS 1.00000 FEET
THE PRESENT LENGTH SEGMENT IS 0.50000 FEET

****
THE PHYSICAL PROPERTIES ARE BASED ON THE BULK TEMPERATURE OF
THE PAST LENGTH SEGMENT WHICH IS 640.0 F

THE DENSITY IS 37.719 LBM/FT3
THE VISCOSITY IS 0.11510E-03 LBM/FT-S
THE THERMAL CONDUCTIVITY IS 0.17528E-04 BTU/S-FT-F
THE HEAT CAPACITY IS 0.77450BTU/LBM-F

****

THE REYNOLDS NUMBER IS 62119.83

****
THE AVERAGE VELOCITY FOR THE PRESENT LENGTH IS 0.37912E 01 FT/S
THE VELOCITY CORRECTION FACTOR IS 0.13902E 01

THE BULK TEMPERATURE FOR THE PRESENT LENGTH IS 643.86035 DEGREES F

THE OUTSIDE TUBE WALL TEMPERATURE IS 0.85194E 03DEGREES F
THE HEAT FLUX FOR THIS LENGTH SEGMENT IS 0.38307E 05 BTU/HR FT2

****

RADIUS	VELOCITY		TEMPERATURE		EDDY DIFFUSIVITY
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT
FT	FT/S	FT/S	DEGREES F	DEGREES F	FT2/S
0.0250000	.0000E 00	.0000E 00	810.0000	811.6665	.0000E 00 *** WALL
0.0249438	.3395E 00	.3395E 00	640.0000	777.5623	.3817E-07
0.0243202	.2648E 01	.2648E 01	640.0000	662.1560	.4185E-04
0.0236966	.2955E 01	.2955E 01	640.0000	654.0842	.1425E-03
0.0230730	.3139E 01	.3139E 01	640.0000	650.3616	.2233E-03
0.0224494	.3272E 01	.3272E 01	640.0000	648.0452	.3053E-03
0.0218258	.3375E 01	.3375E 01	640.0000	646.4438	.3877E-03
0.0212022	.3460E 01	.3460E 01	640.0000	645.2659	.4705E-03
0.0205786	.3531E 01	.3531E 01	640.0000	644.3618	.5533E-03
0.0199550	.3594E 01	.3594E 01	640.0000	643.6479	.6364E-03
0.0193314	.3649E 01	.3649E 01	640.0000	643.0720	.7195E-03
0.0187078	.3698E 01	.3698E 01	640.0000	642.5981	.8027E-03
0.0180842	.3743E 01	.3743E 01	640.0000	642.2019	.8859E-03
0.0174606	.3783E 01	.3783E 01	640.0000	641.8667	.9691E-03
0.0168370	.3821E 01	.3821E 01	640.0000	641.5806	.1052E-02
0.0162134	.3856E 01	.3856E 01	640.0000	641.3342	.1136E-02
0.0155898	.3888E 01	.3888E 01	640.0000	641.1196	.1219E-02
0.0149662	.3918E 01	.3918E 01	640.0000	640.9319	.1302E-02
0.0143426	.3947E 01	.3947E 01	640.0000	640.7664	.1386E-02
0.0137190	.3973E 01	.3973E 01	640.0000	640.6206	.1469E-02
0.0130954	.3999E 01	.3999E 01	640.0000	640.4912	.1552E-02
0.0124718	.4023E 01	.4023E 01	640.0000	640.3757	.1636E-02
0.0118482	.4046E 01	.4046E 01	640.0000	640.2739	.1719E-02
0.0112246	.4068E 01	.4068E 01	640.0000	640.1851	.1802E-02
0.0106011	.4089E 01	.4089E 01	640.0000	640.1084	.1886E-02
0.0099775	.4109E 01	.4109E 01	640.0000	640.0417	.1969E-02
0.0093539	.4128E 01	.4128E 01	640.0000	640.0000	.2053E-02
0.0087303	.4146E 01	.4146E 01	640.0000	640.0000	.2136E-02
0.0081067	.4164E 01	.4164E 01	640.0000	640.0000	.2219E-02
0.0074831	.4181E 01	.4181E 01	640.0000	640.0000	.2303E-02
0.0068595	.4198E 01	.4198E 01	640.0000	640.0000	.2386E-02
0.0062359	.4214E 01	.4214E 01	640.0000	640.0000	.2469E-02
0.0056123	.4229E 01	.4229E 01	640.0000	640.0000	.2553E-02
0.0049887	.4244E 01	.4244E 01	640.0000	640.0000	.2637E-02
0.0043651	.4258E 01	.4258E 01	640.0000	640.0000	.2720E-02
0.0037415	.4273E 01	.4273E 01	640.0000	640.0000	.2803E-02
0.0031179	.4286E 01	.4286E 01	640.0000	640.0000	.2887E-02
0.0024943	.4299E 01	.4299E 01	640.0000	640.0000	.2970E-02
0.0018707	.4312E 01	.4312E 01	640.0000	640.0000	.3053E-02
0.0012471	.4325E 01	.4325E 01	640.0000	640.0000	.3136E-02
0.0006235	.4337E 01	.4337E 01	640.0000	640.0000	.3220E-02
0.0000000	.4349E 01	.4349E 01	640.0000	640.0000	.3220E-02

****
****

****

THE PRESENT TIME IS 0.0 HOURS

****

THE PAST LENGTH SEGMENT IS 0.50000 FEET
THE PRESENT LENGTH SEGMENT IS 1.00000 FEET

****

THE PHYSICAL PROPERTIES ARE BASED ON THE BULK TEMPERATURE OF
THE PAST LENGTH SEGMENT WHICH IS 643.9 F

THE DENSITY IS 37.719 LBM/FT3
THE VISCOSITY IS 0.11510E-03 LBM/FT-S
THE THERMAL CONDUCTIVITY IS 0.17528E-04 BTU/S-FT-F
THE HEAT CAPACITY IS 0.77450BTU/LBM-F

****

THE REYNOLDS NUMBER IS 62149.83

****

THE AVERAGE VELOCITY FOR THE PRESENT LENGTH IS 0.37912E 01 FT/S
THE VELOCITY CORRECTION FACTOR IS 0.13902E 01

THE BULK TEMPERATURE FOR THE PRESENT LENGTH IS 647.64843 DEGREES F

THE OUTSIDE TUBE WALL TEMPERATURE IS 0.85281E 03DEGREES F
THE HEAT FLUX FOR THIS LENGTH SEGMENT IS 0.37590E 05 BTU/HR FT2

****

RADIUS	VELOCITY		TEMPERATURE		EDDY DIFFUSIVITY	
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT	
FT	FT/S	FT/S	DEGREES F	DEGREES F	FT2/S	
0.0250000	.0000E 00	.0000E 00	811.6665	813.3333	.0000E 00	*** WALL
0.0249438	.3395E 00	.3395E 00	777.5623	779.8674	.3817E-07	
0.0243202	.2648E 01	.2648E 01	662.1560	672.7727	.4185E-04	
0.0236966	.2955E 01	.2955E 01	654.0842	663.5967	.1425E-03	
0.0230730	.3139E 01	.3139E 01	650.3616	658.8665	.2233E-03	
0.0224494	.3272E 01	.3272E 01	648.0452	655.6472	.3053E-03	
0.0218258	.3375E 01	.3375E 01	646.4438	653.2527	.3877E-03	
0.0212022	.3460E 01	.3461E 01	645.2659	651.3782	.4705E-03	
0.0205786	.3531E 01	.3531E 01	644.3618	649.8616	.5533E-03	
0.0199550	.3594E 01	.3594E 01	643.6479	648.6057	.6364E-03	
0.0193314	.3649E 01	.3649E 01	643.0720	647.5476	.7195E-03	
0.0187078	.3698E 01	.3698E 01	642.5981	646.6460	.8027E-03	
0.0180842	.3743E 01	.3743E 01	642.2019	645.8696	.8859E-03	
0.0174606	.3783E 01	.3783E 01	641.8667	645.1956	.9691E-03	
0.0168370	.3821E 01	.3821E 01	641.5806	644.6074	.1052E-02	
0.0162134	.3856E 01	.3856E 01	641.3342	644.0916	.1136E-02	
0.0155898	.3888E 01	.3888E 01	641.1196	643.6377	.1219E-02	
0.0149662	.3918E 01	.3918E 01	640.9319	643.2371	.1302E-02	
0.0143426	.3947E 01	.3947E 01	640.7664	642.8826	.1386E-02	
0.0137190	.3973E 01	.3973E 01	640.6206	642.5686	.1469E-02	
0.0130954	.3999E 01	.3999E 01	640.4912	642.2905	.1552E-02	
0.0124718	.4023E 01	.4023E 01	640.3757	642.0442	.1636E-02	
0.0118482	.4046E 01	.4046E 01	640.2739	641.8267	.1719E-02	
0.0112246	.4068E 01	.4068E 01	640.1851	641.6345	.1802E-02	
0.0106011	.4089E 01	.4089E 01	640.1084	641.4651	.1886E-02	
0.0099775	.4109E 01	.4109E 01	640.0417	641.3167	.1969E-02	
0.0093539	.4128E 01	.4128E 01	640.0000	641.1714	.2053E-02	
0.0087303	.4146E 01	.4146E 01	640.0000	641.0095	.2136E-02	
0.0081067	.4164E 01	.4164E 01	640.0000	640.8696	.2219E-02	
0.0074831	.4181E 01	.4181E 01	640.0000	640.7488	.2303E-02	
0.0068595	.4198E 01	.4198E 01	640.0000	640.6455	.2386E-02	
0.0062359	.4214E 01	.4214E 01	640.0000	640.5583	.2469E-02	
0.0056123	.4229E 01	.4229E 01	640.0000	640.4854	.2553E-02	
0.0049887	.4244E 01	.4244E 01	640.0000	640.4253	.2637E-02	
0.0043651	.4258E 01	.4258E 01	640.0000	640.3770	.2720E-02	
0.0037415	.4273E 01	.4273E 01	640.0000	640.3389	.2803E-02	
0.0031179	.4286E 01	.4286E 01	640.0000	640.3103	.2887E-02	
0.0024943	.4299E 01	.4299E 01	640.0000	640.2898	.2970E-02	
0.0018707	.4312E 01	.4312E 01	640.0000	640.2766	.3053E-02	
0.0012471	.4325E 01	.4325E 01	640.0000	640.2693	.3136E-02	
0.0006235	.4337E 01	.4337E 01	640.0000	640.2671	.3220E-02	
0.0000000	.4349E 01	.4349E 01	640.0000	640.2671	.3220E-02	

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THE PRESENT TIME IS 0.0 HOURS

THE PAST LENGTH SEGMENT IS 4.00000 FEET
THE PRESENT LENGTH SEGMENT IS 4.50000 FEET

THE PHYSICAL PROPERTIES ARE BASED ON THE BULK TEMPERATURE OF THE PAST LENGTH SEGMENT WHICH IS 657.9 F

THE DENSITY IS 37.390 LBM/FT3
THE VISCOSITY IS 0.10542E-03 LBM/FT-S
THE THERMAL CONDUCTIVITY IS 0.17421E-04 BTU/S-FT-F
THE HEAT CAPACITY IS 0.78402BTU/LBM-F

THE REYNOLDS NUMBER IS 67823.00

THE AVERAGE VELOCITY FOR THE PRESENT LENGTH IS 0.38246E 01 FT/S
THE VELOCITY CORRECTION FACTOR IS 0.13753E 01

THE BULK TEMPERATURE FOR THE PRESENT LENGTH IS 659.44482 DEGREES F

THE OUTSIDE TUBE WALL TEMPERATURE IS 0.84116E 03DEGREES F
THE HEAT FLUX FOR THIS LENGTH SEGMENT IS 0.15912E 05 BTU/HR FT2

RADIUS	VELOCITY		TEMPERATURE		EDDY DIFFUSIVITY	
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT	
FT	FT/S	FT/S	DEGREES F	DEGREES F	FT2/S	
0.0250000	.0000E 00	.0000E 00	823.3333	824.9998	.0000E 00	*** WALL
0.0249485	.3421E 00	.3424E 00	809.7014	811.9392	.3244E-07	
0.0243248	.2676E 01	.2679E 01	694.6499	695.9976	.4497E-04	
0.0237011	.2984E 01	.2987E 01	680.9524	682.5947	.1416E-03	
0.0230774	.3169E 01	.3172E 01	673.9963	675.7827	.2222E-03	
0.0224537	.3301E 01	.3304E 01	669.3523	671.1997	.3040E-03	
0.0218300	.3404E 01	.3407E 01	665.9390	667.7998	.3862E-03	
0.0212062	.3489E 01	.3492E 01	663.2852	665.1318	.4688E-03	
0.0205825	.3561E 01	.3564E 01	661.1443	662.9626	.5515E-03	
0.0199588	.3623E 01	.3626E 01	659.3713	661.1558	.6344E-03	
0.0193351	.3678E 01	.3681E 01	657.8735	659.6250	.7173E-03	
0.0187114	.3727E 01	.3730E 01	656.5925	658.3081	.8003E-03	
0.0180877	.3771E 01	.3775E 01	655.4824	657.1643	.8833E-03	
0.0174640	.3812E 01	.3815E 01	654.5095	656.1653	.9663E-03	
0.0168402	.3850E 01	.3853E 01	653.6538	655.2852	.1049E-02	
0.0162165	.3884E 01	.3887E 01	652.8962	654.5054	.1133E-02	
0.0155928	.3917E 01	.3920E 01	652.2246	653.8103	.1216E-02	
0.0149691	.3947E 01	.3950E 01	651.6273	653.1885	.1299E-02	
0.0143454	.3975E 01	.3978E 01	651.0950	652.6299	.1382E-02	
0.0137217	.4002E 01	.4005E 01	650.6216	652.1260	.1465E-02	
0.0130980	.4027E 01	.4030E 01	650.1970	651.6738	.1548E-02	
0.0124742	.4051E 01	.4054E 01	649.8201	651.2639	.1632E-02	
0.0118505	.4074E 01	.4077E 01	649.4871	650.8916	.1715E-02	
0.0112268	.4096E 01	.4099E 01	649.1917	650.5571	.1798E-02	
0.0106031	.4117E 01	.4120E 01	648.9319	650.2554	.1881E-02	
0.0099794	.4137E 01	.4140E 01	648.7043	649.9836	.1964E-02	
0.0093557	.4156E 01	.4159E 01	648.4915	649.7537	.2048E-02	
0.0087320	.4175E 01	.4178E 01	648.2737	649.5798	.2131E-02	
0.0081082	.4192E 01	.4195E 01	648.0874	649.4219	.2214E-02	
0.0074845	.4209E 01	.4212E 01	647.9272	649.2810	.2297E-02	
0.0068608	.4226E 01	.4229E 01	647.7891	649.1572	.2380E-02	
0.0062371	.4242E 01	.4245E 01	647.6716	649.0496	.2464E-02	
0.0056134	.4257E 01	.4260E 01	647.5742	648.9556	.2547E-02	
0.0049897	.4272E 01	.4275E 01	647.4934	648.8762	.2630E-02	
0.0043660	.4287E 01	.4289E 01	647.4268	648.8113	.2713E-02	
0.0037422	.4301E 01	.4304E 01	647.3735	648.7590	.2796E-02	
0.0031185	.4314E 01	.4317E 01	647.3320	648.7188	.2880E-02	
0.0024948	.4327E 01	.4330E 01	647.2998	648.6907	.2963E-02	
0.0018711	.4340E 01	.4343E 01	647.2776	648.6719	.3046E-02	
0.0012474	.4353E 01	.4356E 01	647.2644	648.6606	.3130E-02	
0.0006237	.4365E 01	.4368E 01	647.2585	648.6563	.3212E-02	
0.0000000	.4377E 01	.4380E 01	647.2585	648.6550	.3212E-02	

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THE PRESENT TIME IS 0.0 HOURS

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THE PAST LENGTH SEGMENT IS 8.50000 FEET
THE PRESENT LENGTH SEGMENT IS 9.00000 FEET

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THE PHYSICAL PROPERTIES ARE BASED ON THE BULK TEMPERATURE OF
THE PAST LENGTH SEGMENT WHICH IS 673.9 F

THE DENSITY IS 37.064 LBM/FT3
THE VISCOSITY IS 0.96962E-04 LBM/FT-S
THE THERMAL CONDUCTIVITY IS 0.17317E-04 BTU/S-FT-F
THE HEAT CAPACITY IS 0.79829BTU/LBM-F

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THE REYNOLDS NUMBER IS 73740.13

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THE AVERAGE VELOCITY FOR THE PRESENT LENGTH IS 0.38582E 01 FT/S
THE VELOCITY CORRECTION FACTOR IS 0.13614E 01

THE BULK TEMPERATURE FOR THE PRESENT LENGTH IS 675.83911 DEGREES F

THE OUTSIDE TUBE WALL TEMPERATURE IS 0.85962E 03DEGREES F
THE HEAT FLUX FOR THIS LENGTH SEGMENT IS 0.19247E 05 BTU/HR FT2

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RADIUS	VELOCITY		TEMPERATURE		EDDY DIFFUSIVITY	
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT	
FT	FT/S	FT/S	DEGREES F	DEGREES F	FT2/S	
0.0250000	.0000E 00	.0000E 00	838.3338	839.9998	.0000E 00	*** WALL
0.0249526	.3449E 00	.3453E 00	823.4290	825.3779	.2779E-07	
0.0243288	.2707E 01	.2711E 01	716.9509	719.9675	.4801E-04	
0.0237050	.3016E 01	.3020E 01	701.2744	703.7136	.1408E-03	
0.0230812	.3201E 01	.3205E 01	693.1890	695.3977	.2214E-03	
0.0224574	.3333E 01	.3337E 01	687.7551	689.8516	.3030E-03	
0.0218335	.3436E 01	.3440E 01	683.7356	685.7659	.3851E-03	
0.0212097	.3521E 01	.3525E 01	680.5930	682.5784	.4675E-03	
0.0205859	.3592E 01	.3596E 01	678.0464	679.9968	.5501E-03	
0.0199621	.3654E 01	.3658E 01	675.9312	677.8516	.6328E-03	
0.0193383	.3709E 01	.3713E 01	674.1445	676.0330	.7156E-03	
0.0187145	.3758E 01	.3762E 01	672.6111	674.4724	.7984E-03	
0.0180906	.3803E 01	.3807E 01	671.2813	673.1177	.8814E-03	
0.0174668	.3844E 01	.3847E 01	670.1196	671.9304	.9642E-03	
0.0168430	.3881E 01	.3885E 01	669.0977	670.8835	.1047E-02	
0.0162192	.3916E 01	.3919E 01	668.1943	669.9553	.1130E-02	
0.0155954	.3948E 01	.3952E 01	667.3887	669.1318	.1213E-02	
0.0149715	.3978E 01	.3982E 01	666.6707	668.3962	.1296E-02	
0.0143477	.4006E 01	.4010E 01	666.0293	667.7375	.1379E-02	
0.0137239	.4033E 01	.4037E 01	665.4529	667.1489	.1462E-02	
0.0131001	.4059E 01	.4062E 01	664.9353	666.6218	.1545E-02	
0.0124763	.4083E 01	.4086E 01	664.4675	666.1519	.1628E-02	
0.0118525	.4105E 01	.4109E 01	664.0408	665.7383	.1711E-02	
0.0112286	.4127E 01	.4131E 01	663.6570	665.3704	.1795E-02	
0.0106048	.4148E 01	.4152E 01	663.3105	665.0464	.1877E-02	
0.0099810	.4168E 01	.4172E 01	662.9971	664.7634	.1961E-02	
0.0093572	.4187E 01	.4191E 01	662.7266	664.5056	.2044E-02	
0.0087334	.4205E 01	.4209E 01	662.5164	664.2493	.2126E-02	
0.0081095	.4223E 01	.4227E 01	662.3247	664.0305	.2210E-02	
0.0074857	.4240E 01	.4244E 01	662.1528	663.8438	.2293E-02	
0.0068619	.4257E 01	.4260E 01	662.0005	663.6846	.2376E-02	
0.0062381	.4273E 01	.4276E 01	661.8674	663.5498	.2459E-02	
0.0056143	.4288E 01	.4292E 01	661.7517	663.4377	.2542E-02	
0.0049904	.4303E 01	.4307E 01	661.6533	663.3452	.2625E-02	
0.0043666	.4317E 01	.4321E 01	661.5737	663.2678	.2708E-02	
0.0037428	.4331E 01	.4335E 01	661.5093	663.2053	.2791E-02	
0.0031190	.4345E 01	.4349E 01	661.4595	663.1565	.2875E-02	
0.0024952	.4358E 01	.4362E 01	661.4233	663.1194	.2958E-02	
0.0018714	.4371E 01	.4375E 01	661.3987	663.0930	.3040E-02	
0.0012475	.4383E 01	.4387E 01	661.3855	663.0754	.3124E-02	
0.0006237	.4396E 01	.4399E 01	661.3796	663.0671	.3206E-02	
0.0000000	.4408E 01	.4411E 01	661.3774	663.0679	.3206E-02	

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THE ENTIRE LENGTH FOR TIME    0.0 HOURS HAS BEEN COMPLETED

THE AVERAGE FILM TEMPERATURE FOR THE LENGTH IS    809.30 DEGREES F
THE COKE THICKNESS BASED ON THIS TEMPERATURE AT TIME  191.0 IS     0.87890E-03 FT1
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THE PRESENT TIME IS 191.0 HOURS

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THE PAST LENGTH SEGMENT IS 0.00000 FEET
THE PRESENT LENGTH SEGMENT IS 0.50000 FEET

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THE PHYSICAL PROPERTIES ARE BASED ON THE BULK TEMPERATURE OF
THE PAST LENGTH SEGMENT WHICH IS 640.0 F

THE DENSITY IS 37.719 LBM/FT3
THE VISCOSITY IS 0.11510E-03 LBM/FT-S
THE THERMAL CONDUCTIVITY IS 0.17528E-04 BTU/S-FT-F
THE HEAT CAPACITY IS 0.77450BTU/LBM-F

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THE REYNOLDS NUMBER IS 59935.89

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THE AVERAGE VELOCITY FOR THE PRESENT LENGTH IS 0.37912E 01 FT/S
THE VELOCITY CORRECTION FACTOR IS 0.13867E 01

THE BULK TEMPERATURE FOR THE PRESENT LENGTH IS 644.36743 DEGREES F

THE OUTSIDE TUBE WALL TEMPERATURE IS 0.10783E 04DEGREES F
THE HEAT FLUX FOR THIS LENGTH SEGMENT IS 0.41810E 05 BTU/HR FT2

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RADIUS	VELOCITY		TEMPERATURE		EDDY DIFFUSIVITY	
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT	
FT	FT/S	FT/S	DEGREES F	DEGREES F	FT2/S	
0.0241211	.0000E 00	.0000E 00	810.0000	811.6665	.0000E 00	*** WALL
0.0240653	.3417E 00	.3417E 00	640.0000	774.6858	.3868E+07	
0.0234636	.2628E 01	.2628E 01	640.0000	665.1677	.4179E-04	
0.0228620	.2953E 01	.2953E 01	640.0000	656.0923	.1382E-03	
0.0222604	.3138E 01	.3138E 01	640.0000	651.8730	.2165E-03	
0.0216587	.3271E 01	.3271E 01	640.0000	649.2400	.2959E+03	
0.0210571	.3375E 01	.3375E 01	640.0000	647.4150	.3758E-03	
0.0204555	.3460E 01	.3461E 01	640.0000	646.0691	.4559E-03	
0.0198538	.3532E 01	.3532E 01	640.0000	[illegible]	[illegible]	
0.0192522	.3594E 01	.3594E 01	640.0000	644.2158	.6166E-03	
0.0186506	.3649E 01	.3649E 01	640.0000	643.5535	.6971E-03	
0.0180489	.3699E 01	.3699E 01	640.0000	643.0068	.7777E-03	
0.0174473	.3744E 01	.3744E 01	640.0000	642.5493	.8582E-03	
0.0168457	.3785E 01	.3785E 01	640.0000	642.1624	.9390E-03	
0.0162440	.3822E 01	.3822E 01	640.0000	641.8320	.1020E-02	
0.0156424	.3857E 01	.3857E 01	640.0000	641.5474	.1100E-02	
0.0150408	.3890E 01	.3890E 01	640.0000	641.3000	.1181E-02	
0.0144391	.3920E 01	.3920E 01	640.0000	641.0833	.1262E+02	
0.0138375	.3949E 01	.3949E 01	640.0000	640.8933	.1342E-02	
0.0132359	.3975E 01	.3975E 01	640.0000	640.7256	.1423E-02	
0.0126342	.4001E 01	.4001E 01	640.0000	640.5767	.1504E+02	
0.0120326	.4025E 01	.4025E 01	640.0000	640.4453	.1584E-02	
0.0114310	.4048E 01	.4048E 01	640.0000	640.3296	.1665E+02	
0.0108293	.4070E 01	.4070E 01	640.0000	640.2285	.1746E-02	
0.0102277	.4091E 01	.4091E 01	640.0000	640.1409	.1827E-02	
0.0096261	.4111E 01	.4111E 01	640.0000	640.0642	.1908E-02	
0.0090244	.4130E 01	.4130E 01	640.0000	640.0000	.1989E-02	
0.0084228	.4149E 01	.4149E 01	640.0000	640.0000	.2069E-02	
0.0078212	.4167E 01	.4167E 01	640.0000	640.0000	.2150E-02	
0.0072195	.4184E 01	.4184E 01	640.0000	640.0000	.2231E-02	
0.0066179	.4201E 01	.4201E 01	640.0000	640.0000	.2311E-02	
0.0060163	.4217E 01	.4217E 01	640.0000	640.0000	.2392E-02	
0.0054146	.4232E 01	.4232E 01	640.0000	640.0000	.2473E-02	
0.0048130	.4247E 01	.4247E 01	640.0000	640.0000	.2554E-02	
0.0042113	.4262E 01	.4262E 01	640.0000	640.0000	.2635E+02	
0.0036097	.4276E 01	.4276E 01	640.0000	640.0000	.2715E-02	
0.0030081	.4289E 01	.4289E 01	640.0000	640.0000	.2797E-02	
0.0024065	.4303E 01	.4303E 01	640.0000	640.0000	.2877E-02	
0.0018048	.4316E 01	.4316E 01	640.0000	640.0000	.2957E-02	
0.0012032	.4328E 01	.4328E 01	640.0000	640.0000	.3039E-02	
0.0006016	.4341E 01	.4341E 01	640.0000	640.0000	.3119E-02	
0.0000000	.4353E 01	.4353E 01	640.0000	640.0000	.3119E-02	

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THE PRESENT TIME IS 19160 HOURS

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THE PAST LENGTH SEGMENT IS 0.50000 FEET
THE PRESENT LENGTH SEGMENT IS 1.00000 FEET

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THE PHYSICAL PROPERTIES ARE BASED ON THE BULK TEMPERATURE OF
THE PAST LENGTH SEGMENT WHICH IS 644.4 F

THE DENSITY IS 37.719 LBM/FT3
THE VISCOSITY IS 0.11510E-03 LBM/FT-S
THE THERMAL CONDUCTIVITY IS 0.17528E-04 BTU/S-FT-F
THE HEAT CAPACITY IS 0.77450BTU/LBM-F

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THE REYNOLDS NUMBER IS 59985.89

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THE AVERAGE VELOCITY FOR THE PRESENT LENGTH IS 0.37912E 01 FT/S
THE VELOCITY CORRECTION FACTOR IS 0.13867E 01

THE BULK TEMPERATURE FOR THE PRESENT LENGTH IS 648.60253 DEGREES F

THE OUTSIDE TUBE WALL TEMPERATURE IS 0.10718E 04DEGREES F
THE HEAT FLUX FOR THIS LENGTH SEGMENT IS 0.40543E 05 BTU/HR FT2 +

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RADIUS	VELOCITY		TEMPERATURE		EDDY DIFFUSIVITY	
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT	
FT	FT/S	FT/S	DEGREES F	DEGREES F	FT2/S	
0.0241211	.0000E 00	.0000E 00	811.6665	813.3333	.0000E 00	*** WALL
0.0240653	.3417E 00	.3417E 00	774.6858	777.4731	.3868E-07	
0.0234636	.2628E 01	.2628E 01	665.1677	676.6687	.4179E-04	
0.0228620	.2953E 01	.2953E 01	656.0923	666.5212	.1382E-03	
0.0222604	.3138E 01	.3138E 01	651.8730	661.2532	.2165E-03	
0.0216587	.3271E 01	.3271E 01	649.2430	657.6609	.2959E-03	
0.0210571	.3375E 01	.3375E 01	647.4150	654.9839	.3758E-03	
0.0204555	.3460E 01	.3460E 01	646.0691	652.8845	.4559E-03	
0.0198538	.3532E 01	.3532E 01	645.0347	651.1831	.5362E-03	
0.0192522	.3594E 01	.3594E 01	644.2158	649.7722	.6166E-03	
0.0186506	.3649E 01	.3649E 01	643.5535	648.5828	.6971E-03	
0.0180489	.3699E 01	.3699E 01	643.0068	647.5679	.7777E-03	
0.0174473	.3744E 01	.3744E 01	642.5493	646.6929	.8582E-03	
0.0168457	.3785E 01	.3785E 01	642.1624	645.9326	.9390E-03	
0.0162440	.3822E 01	.3822E 01	641.8320	645.2681	.1020E-02	
0.0156424	.3857E 01	.3857E 01	641.5474	644.6851	.1100E-02	
0.0150408	.3890E 01	.3890E 01	641.3003	644.1711	.1181E-02	
0.0144391	.3920E 01	.3920E 01	641.0833	643.7173	.1262E-02	
0.0138375	.3949E 01	.3949E 01	640.8933	643.3152	.1342E-02	
0.0132359	.3975E 01	.3975E 01	640.7256	642.9587	.1423E-02	
0.0126342	.4001E 01	.4001E 01	640.5767	642.6433	.1504E-02	
0.0120326	.4025E 01	.4025E 01	640.4453	642.3638	.1584E-02	
0.0114310	.4048E 01	.4048E 01	640.3296	642.1160	.1665E-02	
0.0108293	.4070E 01	.4070E 01	640.2285	641.8970	.1746E-02	
0.0102277	.4091E 01	.4091E 01	640.1409	641.7039	.1827E-02	
0.0096261	.4111E 01	.4111E 01	640.0642	641.5342	.1908E-02	
0.0090244	.4130E 01	.4130E 01	640.0000	641.3833	.1989E-02	
0.0084228	.4149E 01	.4149E 01	640.0000	641.1965	.2069E-02	
0.0078212	.4167E 01	.4167E 01	640.0000	641.0349	.2150E-02	
0.0072195	.4184E 01	.4184E 01	640.0000	640.8958	.2231E-02	
0.0066179	.4201E 01	.4201E 01	640.0000	640.7771	.2311E-02	
0.0060163	.4217E 01	.4217E 01	640.0000	640.6765	.2392E-02	
0.0054146	.4232E 01	.4232E 01	640.0000	640.5920	.2473E-02	
0.0048130	.4247E 01	.4247E 01	640.0000	640.5222	.2554E-02	
0.0042113	.4262E 01	.4262E 01	640.0000	640.4651	.2635E-02	
0.0036097	.4276E 01	.4276E 01	640.0000	640.4199	.2715E-02	
0.0030081	.4289E 01	.4289E 01	640.0000	640.3853	.2797E-02	
0.0024065	.4303E 01	.4303E 01	640.0000	640.3604	.2877E-02	
0.0018048	.4316E 01	.4316E 01	640.0000	640.3438	.2957E-02	
0.0012032	.4328E 01	.4328E 01	640.0000	640.3345	.3039E-02	
0.0006016	.4341E 01	.4341E 01	640.0000	640.3311	.3119E-02	
0.0000000	.4353E 01	.4353E 01	640.0000	640.3308	.3119E-02	

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THE PRESENT TIME IS 191.0 HOURS

THE PAST LENGTH SEGMENT IS 4.00000 FEET
THE PRESENT LENGTH SEGMENT IS 4.50000 FEET

THE PHYSICAL PROPERTIES ARE BASED ON THE BULK TEMPERATURE OF THE PAST LENGTH SEGMENT WHICH IS 656.8 F

THE DENSITY IS 37.410 LBM/FT3
THE VISCOSITY IS 0.10600E-03 LBM/FT-S
THE THERMAL CONDUCTIVITY IS 0.17428E-04 BTU/S-FT-F
THE HEAT CAPACITY IS 0.78342BTU/LBM-F

THE REYNOLDS NUMBER IS 65081.18

THE AVERAGE VELOCITY FOR THE PRESENT LENGTH IS 0.38225E 01 FT/S
THE VELOCITY CORRECTION FACTOR IS 0.13724E 01

THE BULK TEMPERATURE FOR THE PRESENT LENGTH IS 658.24023 DEGREES F

THE OUTSIDE TUBE WALL TEMPERATURE IS 0.91632E 03DEGREES F
THE HEAT FLUX FOR THIS LENGTH SEGMENT IS 0.14417E 05 BTU/HR FT2

RADIUS	VELOCITY		TEMPERATURE		EDDY DIFFUSIVITY	
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT	
FT	FT/S	FT/S	DEGREES F	DEGREES F	FT2/S	
0.0241211	.0000E 00	.0000E 00	823.3333	824.9998	.0000E 00	*** WALL
0.0240697	.3442E 00	.3444E 00	810.9133	813.1841	.3346E-07	
0.0234679	.2672E 01	.2674E 01	690.5640	691.6123	.4231E-04	
0.0228662	.2980E 01	.2983E 01	677.9307	679.3357	.1373E-03	
0.0222644	.3165E 01	.3168E 01	671.4268	673.2405	.2155E-03	
0.0216627	.3298E 01	.3301E 01	667.1924	669.0298	.2946E-03	
0.0210610	.3402E 01	.3404E 01	664.1282	665.8572	.3743E-03	
0.0204592	.3487E 01	.3489E 01	661.7751	663.3381	.4542E-03	
0.0198575	.3558E 01	.3561E 01	659.9019	661.2632	.5343E-03	
0.0192557	.3621E 01	.3624E 01	658.2563	659.6252	.6146E-03	
0.0186540	.3676E 01	.3679E 01	656.7954	658.3059	.6949E-03	
0.0180523	.3725E 01	.3728E 01	655.5662	657.1470	.7753E-03	
0.0174505	.3770E 01	.3773E 01	654.5154	656.1257	.8556E-03	
0.0168488	.3811E 01	.3814E 01	653.6042	655.2253	.9362E-03	
0.0162470	.3848E 01	.3851E 01	652.8088	654.4265	.1017E-02	
0.0156453	.3883E 01	.3886E 01	652.1096	653.7151	.1097E-02	
0.0150435	.3916E 01	.3918E 01	651.4929	653.0774	.1177E-02	
0.0144418	.3946E 01	.3949E 01	650.9446	652.5078	.1258E-02	
0.0138401	.3975E 01	.3977E 01	650.4583	651.9946	.1339E-02	
0.0132383	.4001E 01	.4004E 01	650.0247	651.5330	.1419E-02	
0.0126366	.4027E 01	.4030E 01	649.6404	651.1150	.1500E-02	
0.0120348	.4051E 01	.4054E 01	649.2998	650.7375	.1580E-02	
0.0114331	.4074E 01	.4077E 01	648.9963	650.3977	.1661E-02	
0.0108313	.4096E 01	.4099E 01	648.7292	650.0913	.1742E-02	
0.0102296	.4117E 01	.4119E 01	648.4973	649.8125	.1822E-02	
0.0096279	.4137E 01	.4140E 01	648.2957	649.5598	.1902E-02	
0.0090261	.4156E 01	.4159E 01	648.1177	649.3350	.1983E-02	
0.0084244	.4175E 01	.4177E 01	647.9116	649.1851	.2064E-02	
0.0078226	.4192E 01	.4195E 01	647.7358	649.0471	.2144E-02	
0.0072209	.4210E 01	.4212E 01	647.5859	648.9231	.2225E-02	
0.0066191	.4226E 01	.4229E 01	647.4583	648.8132	.2305E-02	
0.0060174	.4242E 01	.4245E 01	647.3521	648.7158	.2386E-02	
0.0054157	.4257E 01	.4260E 01	647.2637	648.6313	.2467E-02	
0.0048139	.4272E 01	.4275E 01	647.1909	648.5586	.2547E-02	
0.0042122	.4287E 01	.4290E 01	647.1309	648.4983	.2628E-02	
0.0036104	.4301E 01	.4304E 01	647.0828	648.4497	.2709E-02	
0.0030087	.4315E 01	.4317E 01	647.0447	648.4131	.2789E-02	
0.0024069	.4328E 01	.4331E 01	647.0176	648.3848	.2870E-02	
0.0018052	.4341E 01	.4344E 01	646.9988	648.3652	.2950E-02	
0.0012035	.4354E 01	.4356E 01	646.9880	648.3535	.3030E-02	
0.0006017	.4366E 01	.4368E 01	646.9844	648.3477	.3112E-02	
0.0000000	.4378E 01	.4380E 01	646.9846	648.3469	.3112E-02	

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THE PRESENT TIME IS 19160 HOURS

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THE PAST LENGTH SEGMENT IS 8.50000 FEET
THE PRESENT LENGTH SEGMENT IS 9.00000 FEET

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THE PHYSICAL PROPERTIES ARE BASED ON THE BULK TEMPERATURE OF
THE PAST LENGTH SEGMENT WHICH IS 672.3 F

THE DENSITY IS 37.102 LBM/FT3
THE VISCOSITY IS 0.97891E-04 LBM/FT-S
THE THERMAL CONDUCTIVITY IS 0.17329E-04 BTU/S-FT-F
THE HEAT CAPACITY IS 0.79223BTU/LBM-F

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THE REYNOLDS NUMBER IS 70472.31

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THE AVERAGE VELOCITY FOR THE PRESENT LENGTH IS 0.38542E 01 FT/S
THE VELOCITY CORRECTION FACTOR IS 0.13591E 01

THE BULK TEMPERATURE FOR THE PRESENT LENGTH IS 673.92822 DEGREES F

THE OUTSIDE TUBE WALL TEMPERATURE IS 0.95621E 03DEGREES F
THE HEAT FLUX FOR THIS LENGTH SEGMENT IS 0.18325E 05 BTU/HR FT2

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RADIUS	VELOCITY		TEMPERATURE		EDDY DIFFUSIVITY
	PREVIOUS	PRESENT	PREVIOUS	PRESENT	PRESENT
FT	FT/S	FT/S	DEGREES F	DEGREES F	FT2/S
0.0241211	.0000E 00	.0000E 00	838.3333	839.9998	.0000E 00 *** WALL
0.0240736	.3469E 00	.3472E 00	824.4517	826.0464	.2888E-07
0.0234718	.2701E 01	.2704E 01	712.4646	715.4636	.4509E-04
0.0228699	.3010E 01	.3014E 01	697.6826	700.1038	.1366E-03
0.0222681	.3195E 01	.3199E 01	690.1980	692.1934	.2146E-03
0.0216662	.3328E 01	.3332E 01	685.0823	686.9905	.2936E-03
0.0210644	.3432E 01	.3435E 01	681.2678	683.1863	.3732E-03
0.0204625	.3516E 01	.3520E 01	678.2588	680.2434	.4530E-03
0.0198607	.3588E 01	.3592E 01	675.7871	677.8936	.5330E-03
0.0192588	.3651E 01	.3654E 01	673.8066	675.8696	.6131E-03
0.0186570	.3706E 01	.3709E 01	672.1875	674.1008	.6933E-03
0.0180552	.3755E 01	.3759E 01	670.7712	672.6106	.7735E-03
0.0174533	.3800E 01	.3803E 01	669.5298	671.3306	.8538E-03
0.0168515	.3840E 01	.3844E 01	668.4397	670.2151	.9341E-03
0.0162496	.3878E 01	.3882E 01	667.4775	669.2334	.1014E-02
0.0156478	.3913E 01	.3916E 01	666.6245	668.3647	.1095E-02
0.0150459	.3945E 01	.3949E 01	665.8665	667.5918	.1175E-02
0.0144441	.3979E 01	.3979E 01	665.1912	666.9006	.1256E-02
0.0138423	.4004E 01	.4008E 01	664.5842	666.2859	.1336E-02
0.0132404	.4031E 01	.4034E 01	664.0410	665.7349	.1416E-02
0.0126386	.4056E 01	.4063E 01	663.5522	665.2427	.1497E-02
0.0120367	.4080E 01	.4084E 01	663.1111	664.8040	.1577E-02
0.0114349	.4103E 01	.4107E 01	662.7144	664.4128	.1658E-02
0.0108330	.4125E 01	.4129E 01	662.3572	664.0662	.1738E-02
0.0102312	.4146E 01	.4150E 01	662.0330	663.7627	.1818E-02
0.0096294	.4166E 01	.4170E 01	661.7380	663.4998	.1899E-02
0.0090275	.4185E 01	.4189E 01	661.4734	663.2698	.1979E-02
0.0084257	.4204E 01	.4207E 01	661.2871	663.0195	.2060E-02
0.0078238	.4221E 01	.4225E 01	661.1160	662.8074	.2141E-02
0.0072220	.4239E 01	.4242E 01	660.9602	662.6282	.2221E-02
0.0066201	.4255E 01	.4259E 01	660.8240	662.4739	.2302E-02
0.0060183	.4271E 01	.4275E 01	660.7024	662.3457	.2382E-02
0.0054165	.4286E 01	.4290E 01	660.5967	662.2388	.2462E-02
0.0048146	.4301E 01	.4305E 01	660.5063	662.1506	.2542E-02
0.0042128	.4316E 01	.4319E 01	660.4314	662.0786	.2623E-02
0.0036109	.4330E 01	.4333E 01	660.3726	662.0193	.2703E-02
0.0030091	.4344E 01	.4347E 01	660.3276	661.9726	.2785E-02
0.0024073	.4357E 01	.4360E 01	660.2939	661.9385	.2864E-02
0.0018054	.4370E 01	.4373E 01	660.2710	661.9150	.2945E-02
0.0012036	.4382E 01	.4386E 01	660.2576	661.9006	.3025E-02
0.0006017	.4395E 01	.4398E 01	660.2510	661.8953	.3106E-02
0.0000000	.4406E 01	.4410E 01	660.2505	661.8950	.3106E-02

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