MATHEMATICAL MODELLING
OF A REFINERY FURNACE

by

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ABSTRACT

In this study, a mathematical model for the multiple fuel fired, Born type refinery furnace is derived in order to find temperature distribution in the furnace and vapor fraction of the charge. The model is solved by the numerical methods using computer programs written by the author.

The model is available for steady-state. The necessary parameters such as air flowrate, molecular weight of flue gas, flue gas flowrate and adiabatic flame temperature which are not present in the data are calculated by material and energy balances.

The furnace is analyzed in two sections with the assumption of one-dimensional heat transfer for gas and charge. The sections are defined according to the dominating heat transfer mechanism from the heat source, which are radiation and convection sections. Radiation section is further divided into three parts according to type of flow of charge and location of tubes in which charge flows that are: (1) single phase flow in tubes on the walls, (2) two phase flow in tubes on the walls, (3) two phase flow in tubes at the ceiling of the radiation section. Both sections are divided into stages corresponding to each row of tubes.

Temperature distribution in the furnace is found by making energy balances in each stage of each section.

Vapor fraction of charge at each stage is evaluated also by energy balances in two phase region.

On the basis of modelling equations a computer program is developed for the furnace which uses an iterative procedure.

Besides obtaining the numerical solutions of the model, the effect of change in input parameters on output conditions are also evaluated.

ÖZET

Bu çalışmada, rafinerilerde kullanılan, sıvı ve gaz yakıtla ateşlenen Born tipi fırınlar için sıcaklık dağılımı ve ısıtılan maddenin buharlaşma miktarını bulmak amacıyla matematiksel model geliştirilmiş ve bu model yazılan bilgisayar programı kullanılarak sayısal metodlarla çözülmüştür.

Model sürekli şartlar içindir. Veriler arasında bulunmayan hava miktarı, baca gazının molekül ağırlığı ve debisi ile alev sıcaklığı genel kütle ve enerji denklikleri ile bulunur.

Fırın, hakim olan ısı transfer mekanizmasına göre radyasyon ve konveksiyon bölgeleri olmak üzere iki bölüm halinde incelenmiştir. Radyasyon bölgesi daha sonra ısıtılan maddenin akış türüne ve içinde geçtiği boruların yerlerine göre üç bölüme ayrılmıştır. Bunlar: (1) duvardaki borulardan tek fazlı akış, (2) duvardaki borulardan çift fazlı akış, (3) tavandaki borulardan çift fazlı akıştır. Her iki bölgede her boru sırasına denk gelen kısımlar ayrılmıştır.

Isı transferinin baca gazları ve ısınan madde için tek yönlü olduğu varsayılmıştır. Sıcaklık dağılımı her kısımda yapılan enerji denklikleri ile bulunmuştur.

Isınan maddenin buharlaşma miktarı ise yalnızca çift fazlı akış bölgesindeki kısımlarda yapılan enerji denklikleriyle bulunur.

Modelin sayısal çözümün yanısıra, girdi dğeişmelerinin çıkış özelliklerine etkisi de incelenmiştir.

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A	Area (m^2)
API	API gravity
C_p	Specific heat (kcal/kg-°K or kcal/kmol-°K)
D	Diameter (m)
D_h	Hydraulic mean diameter (m)
F	Radiation angle factor
G	Mass flowrate (kg/m^2-hr)
h	Heat transfer coefficient (kcal/m^2-°K-hr)
H	Inlet enthalpy (kcal/kg or kcal/kmole)
H_v	Heat of vaporization for petroleum fractions (kcal/kg)
k	Thermal conductivity (kcal/hr-m-°K)
K	Characterization factor for petroleum fractions
L	Length (m)
m	Mole fraction
M	Molar flow (kmole/hr)
MW	Molecular weight
N	Number of tubes
Nu	Nusselt number
P	Pressure (atm)
P_c	Critical pressure (atm)

Pr	Prandtl number
Q	Heat transferred (kcal/hr)
R	Gas constant (atm-m^3/kmole-°K)
Re	Reynolds number
SG	Specific gravity
T	Temperature (°K)
u	Mean velocity (m/s)
W	Mass flow (kg/hr)
x	Vapor mass fraction
X_{tt}	Martinelli parameter
v	Velocity (m/s)
V	Volumetric flow (m^3/hr)
Z	Compressibility factor
α	Void fraction
γ	Surface tension (N/m)
ΔH_r	Heat of combustion reaction (kcal/kmole)
ε	Emissivity
η	Fraction of reradiation from walls
μ	Viscosity (kg/m-hr)
ν	Kinematic viscosity (cs)
ρ	Density (kg/m^3)
σ	Stephan-Boltzman constant (kcal/hr-m^2-$^oK^4$)
ϕ	Radiation exchange factor
ω	Expansion coefficient

Superscripts

n	Number of the stage
t	Theoretical oxygen

Subscripts

a	Air
as	Atomizing steam
B	Boiling point at 1 atm
c	Charge
ch	Combustion heat release
f	Flame
fg	Fuel gas
fo	Fuel oil
g	Gas phase of charge
G	Combustion or flue gas
i	Inlet or inside
ℓ	Liquid phase of charge
o	Outlet or outside
pf	Petroleum fractions
r	Radiation section
s	Surface or stage
sh	Sensible heat
t	Tube
tp	Two phase
tt	Total
w	Water

I. INTRODUCTION

I.A SCOPE OF THE THESIS

In this study, a mathematical model for the multiple fuel fired, Born type refinery furnace is derived. The model is solved by numerical methods using computer programs written by the author.

Thesis is composed of six chapters. In the first chapter introduction is given and it is divided into two parts. The first part gives the scope of the thesis and the second part review of the literature.

The second chapter contains the information about the furnace with design and operation conditions.

The third chapter is the mathematical modelling which explains how the modelling equations are derived from the theoretical equations. It is composed of two parts; first gives the material and energy balances in the combustion chamber and the second gives the derivation of modelling equations for radiation and convection sections.

In the fourth chapter the computer programming is explained in two parts. Algorithm of the programs is given in the first part and explanation of main program, subroutines and functions ~~is~~ are in the second part.

The fifth chapter gives the results that contains temperature distributions of charge and flue (combustion) gas, vapor fraction of charge at each stage, and effect of change in input parameters and heat transfer coefficients on output conditions with evaluation and discussion. Conclusion is given in the sixth chapter.

Derivation of curve fitted equations, integration of radiation shape factor are explained in appendices A and B respectively.

Appendices C, D, E and F contains computer program listing, definition of variables used in programs, data set and sample output.

I.B HEAT TRANSFER IN FURNACES

The optimal design and operation of a furnace requires detailed analysis of components and thermal process taking place [1,2].

If there is sufficient knowledge on the factors which control the flow pattern, the progress of combustion, the transfer of heat by radiation and convection at every point in the system, the problem of modelling an industrial furnace of specified shape and size, fed with fuel and air at specified rates and in a specified pattern may be solved when temperature pattern in the gas space and along the walls can be predicted [1,3,4]. Because the governing heat-transfer mechanism is different in the radiation and convection section, the two are analyzed by different methods.

The convection section recovers additional heat from flue gas at a lower temperature than in radiation section [5]. If the flue gas temperature is greater than 780°K gas radiation must be taken into account [6]. Here, since the primary heat transfer mechanism is convection, the tubes are arranged to create high mass velocities and turbulence in the gas [5]. Tubes having fins and other types of extended surfaces are frequently installed to improve convective heat transfer by increasing surface area [2,5,6]. In the case of narrow tube banks where the reradiation from the refractory walls becomes significant, an appropriate correction is applied to the radiation component of heat transfer coefficient [6].

Since the convection section is nominally an unfired heat exchanger the amount of heat recovery is dictated by the temperature gradient between the temperature levels of flue gas and process fluid. The higher the operating temperature in the process fluid, the exit flue gas temperature must correspondingly be higher. To further reduce flue gas temperature, other forms of secondary heat recovery must be employed; typically these can be steam generation and air preheater [7, 8,9].

The stack system collects and disposes of the flue gas. In natural draft furnaces the stack height provides adequate draft to draw the gas through the radiation and convection sections [5].

The radiation section is defined as the section in which the heat is liberated from combustion of fuel [10] and which the heat transfer is primarily by radiation from hot gases and flame; the walls of the heater also radiate to the tubes but do so only as intermediate reradiating surfaces which, theoretically do not absorb heat by themselves but transmit to tubes all heat received from the products of combustion [11]. The rates of radiant absorption by tube banks from combustion products are affected by four main factors:

1. quantity of heat liberated
2. flame temperature
3. amount of heat absorbing surface
4. effectiveness of the surface.

The radiation from flames and gases of conventional fuel is due to CO_2, H_2O (g), soot and CO but CO is ignored because it is present at a small extent. Radiation from these depends on number of molecules in the path and temperature and because of pressure broadening on the partial pressure of $CO_2 + H_2O$ [4]. Oil fuel tends to give more luminious flame than refinery gas at usual percentage of excess air because of cracking of the oil particles to so of during the combustion period [10].

Radiant heat absorption characteristics of different types of heaters are determined by the geometry of the heater which affects the direct radiation from gases and particularly the reradiation from the bare refractories of the heater envelope. Also characteristics of the different banks in a particular heater may vary considerably with their location in the heater and the angle through which the banks see refractories [12].

Heat transfer by convection to the tubes in the radiant section of petroleum heaters account for only a small amount of heat transferred, especially in high radiant rate furnaces. This convection transfer is more important in low rate furnaces because heat transfer by convection is proportional to ΔT between gas and cold surface, whereas the radiant heat transfer is proportional to $(T_g^4 - T_s^4)$ [10].

When higher accuracy is not required, the furnace can be modelled by the equation derived by Lobo and Evans [10] which is the basis for almost all models published [5]. They have used uniform temperature assumption in their equation, but to obtain uniform radiating gas temperature either the circulation rate of the gases in the firebox must approach to infinity or the burner arrangement must be such that the heat added to the gas envelope is supplied with complete uniformity throughout the radiation section [6].

There are various models [3,4,11,13,14,15,16] developed in the last 30 years to approach a more realistic and detailed model with a smaller number of assumptions and higher accuracy.

II. DESCRIPTION OF THE FURNACE

The furnace is a building of isolation bricks surrounded by a metal construction. It consists of a combustion chamber for heat release and the latter is surrounded by metal tubes. The charge flows inside the tubes absorbing heat both by radiation and convection. Major heat absorption by charge takes place in the radiation section where the tubes are exposed to the radiant effect of flame, hot gases and hot refractory walls [17].

The upper portion of the furnace is the convection section that is placed between the radiation section and the stack. The charge flowing in the tubes, which are staggered along the path of the flowing gas, is heated by the sensible heat of flue gas.

The charge is the bottom distillate of the crude oil distillation tower which is further distilled in the vacuum distillation tower after being heated up. It enters ~~to~~ the furnace around 300°C in liquid phase and leaves around 360°C both in liquid and gas phases. Approximately half of the charge evaporizes.

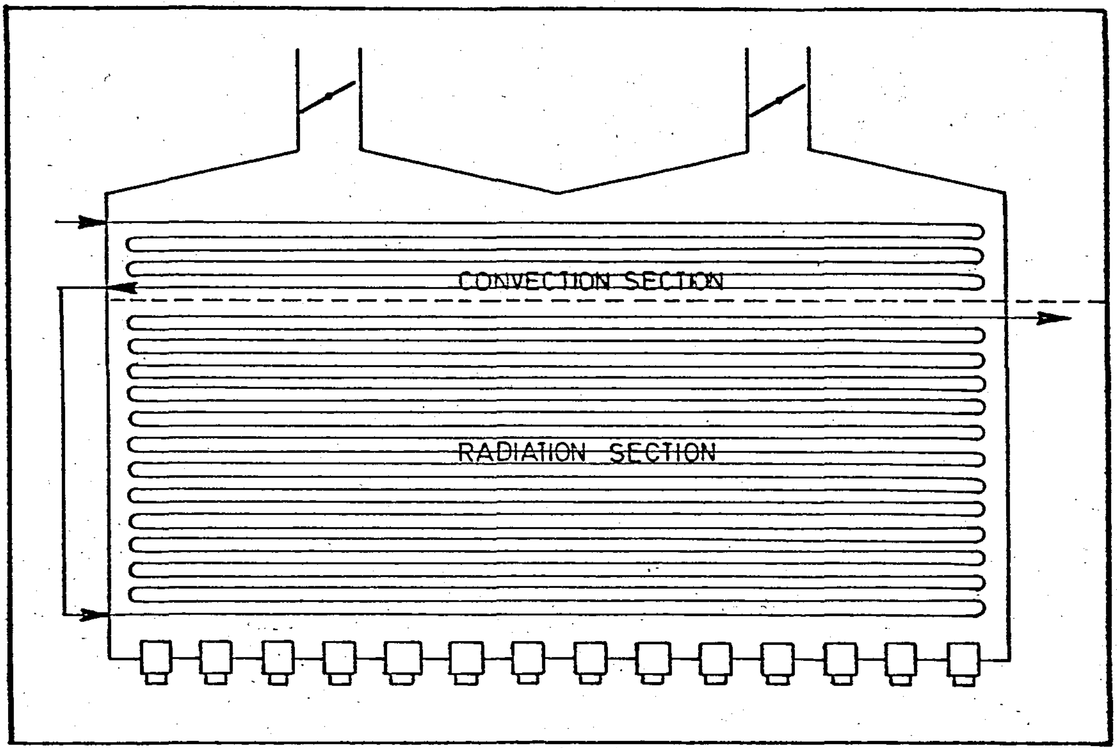

Figure 2.1 Front View of the Furnace [17]

Because the furnace has symmetrical two coil arrangement, the charge enters in two streams which mix after leaving the furnace. The charge enters to the convection section first from top and leaves the bottom part of it, flows down the furnace at the outside from the sides and it enters to the radiation section from the floor level and finally leaves the furnace from the ceiling of radiation section as seen in Figure 2.2.

The necessary energy is supplied by both fuel oil and refinery gas which is mixture of light hydrocarbons, carbon monoxide, carbon dioxide, hydrogen sulfide, hydrogen, oxygen and nitrogen.

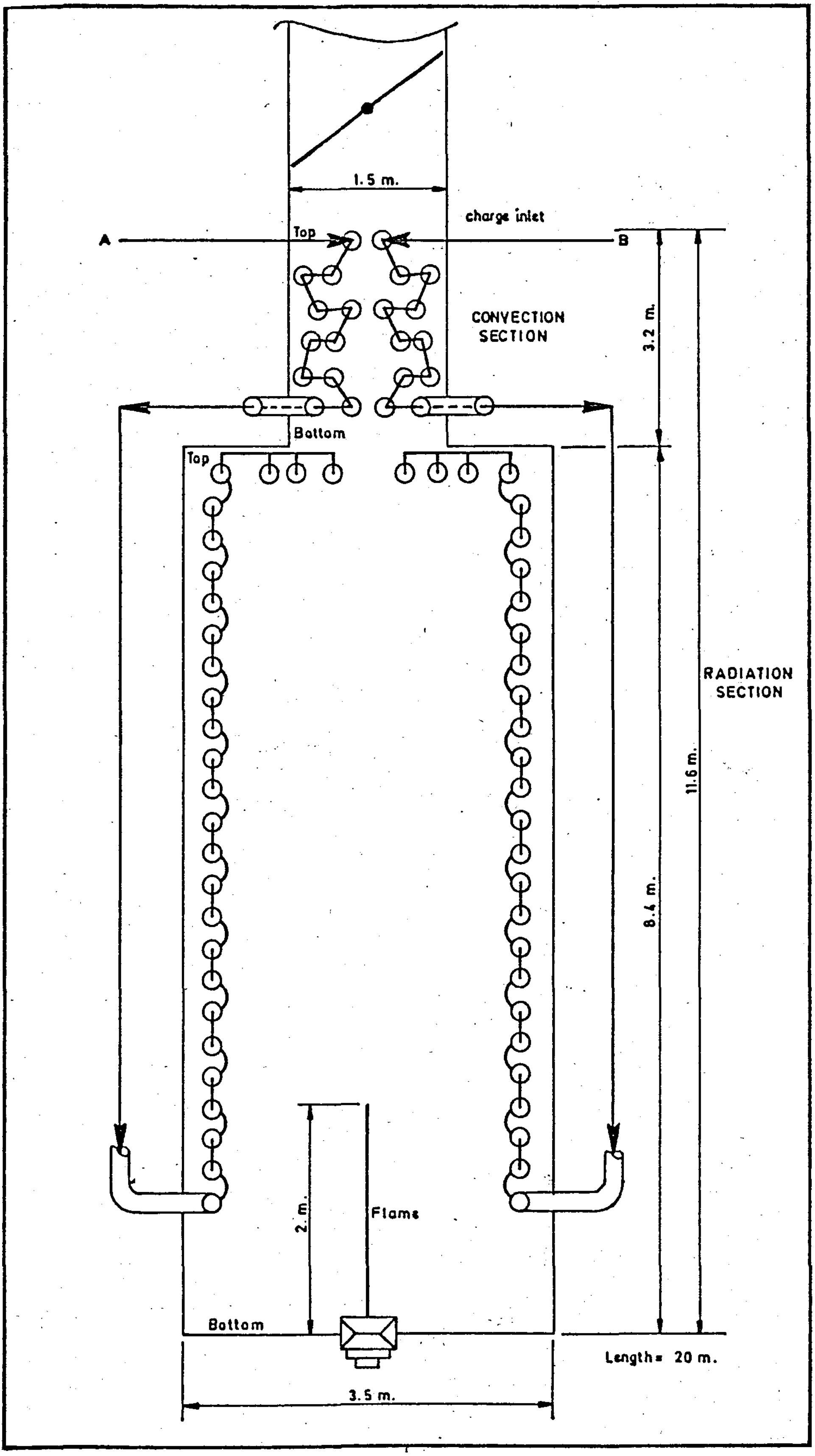

Figure 2.2 Side View of the Furnace [18]

Fuel gas is burned directly, but fuel oil is vaporized prior to combustion. In order to increase rate and area of vaporization, therefore efficiency of fuel oil combustion, it is heated up then atomized.

Fuel, atomizing steam and air are mixed at 14 burners placed on the centerline of the furnace floor which have equal loading of fuel and air in order to obtain uniform temperature distribution in the furnace.

Design conditions are given in Tables 2.1, 2.2 and 2.3 [20].

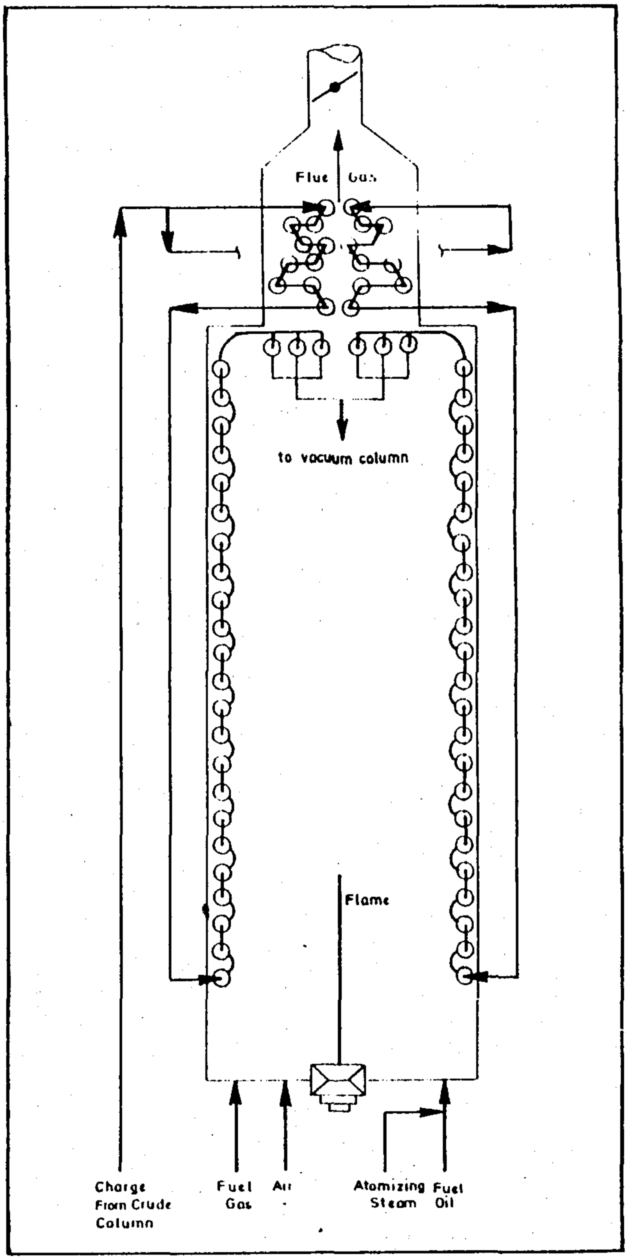

Figure 2 3 Flow Diagram Around the Furnace [19]

TABLE 2.1 - Process Design Conditions

Fluid	Atm. crude tower bottoms
Total heat duty, max case	2168 MM kcal/hr
Number of sections	2
Temp. of flue gas to convection sec.	1088°K
Temp. of flue gas from convection sec.	694°K
Calculated total pressure drop	3.47 atm
Charge flow rate (all liquid)	218665 kg/hr
Charge inlet pressure	3.74 atm
Charge outlet pressure	0.27 atm
Charge inlet temperature	594°K
Charge outlet temperature	694°K
Charge outlet vapor fraction (mass)	0.533
Charge API	16.3

TABLE 2.2 - Combustion Design Condition

Calculated efficiency (LHV)	77.5%	
Radiation loss	2.5%	
Flue gas temp. leaving convection sec.	694°K	
Type of fuel	fuel oil	fuel gas
Excess air	30%	20%
Ambient air temperature	255 to 316°K	302°K
Heating value	10290 kcal/kg	8050 kcal/m^3
Specific gravity	0.98	0.655

TABLE 2.3 - Mechanical Design Conditions

	Radiation section	Convection section
Length	20 m	20 m
Height	8.4 m	3.2 m
Width	3.5 m	1.5 m
Number of coils	2	2
Length of tubes	20 m	20 m
Equiv. length of U-bends	25 pipe dia.	25 pipe dia.
Inside diameter	0.212 m	0.162 m
Outside diameter	0.219 m	0.168 m
Total effective tube surface area	636 m^2	792 m^2
Extended surface	-	studs
Tube spacing	0.3048 m	0.3048 m
Tube position	horizontal	horizontal
Return bends	180° short rad.	180° short rad.
Number of tube rows	24	6 (staggered)
Number of tubes	52	24

III. MATHEMATICAL MODELLING

This chapter contains the explanation of the derivation of modelling equations at steady-state which are the basis for the computerized analysis of the furnace and it is composed of two parts. In the first part general analysis; material and energy balances are made and in the second part detailed analysis for radiation and convection sections is given.

III.A GENERAL MODELLING

The necessary parameters such as air flowrate, molecular weight of flue gas, flue gas flowrate, adiabatic flame temperature and total heat input which are not present in data are modelled in this section by material and energy balances With the assumption of steady-state.

1. Material Balance in the Combustion Chamber

Material balance is needed in order to find air flowrate, flue gas composition, flowrate and molecular weight. The basis for calculations is on hourly rates. The input streams are fuel gas, fuel oil, atomizing steam and air, the output stream is the flue gas.

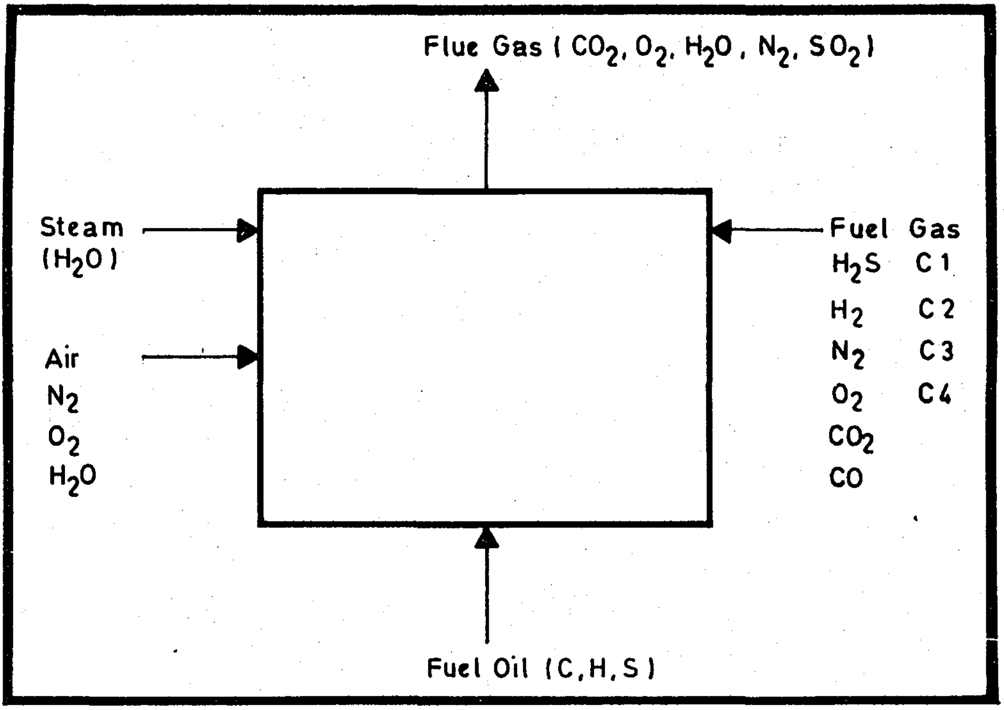

Figure 3.1 Schematic Diagram of Input and Output Streams in Combustion Chamber

To find air flowrate amount of oxygen must be calculated. Assuming complete combustion the reactions are:

for fuel oil

$$H_2 + (1/2)O_2 \rightarrow H_2O$$

$$C + O_2 \rightarrow CO_2$$

$$S + O_2 \rightarrow SO_2$$

for fuel gas

$$H_2S + (3/2)O_2 \rightarrow SO_2 + H_2O$$

$$H_2 + (1/2)O_2 \rightarrow H_2O$$

$$CO + (1/2)O_2 \rightarrow CO_2$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$C_2H_6 + (7/2)O_2 \rightarrow 2CO_2 + 3H_2O$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

$$C_3H_6 + (9/2)O_2 \rightarrow 3CO_2 + 3H_2O$$

$$C_4H_{10} + (13/2)O_2 \rightarrow 4CO_2 + 5H_2O$$

$$C_4H_8 + 6O_2 \rightarrow 4CO_2 + 4H_2O$$

In order to know the amount of reactants weight fraction of hydrogen [21] is calculated from equation (3.1),

$$\%H_2 = 26 - 15(SG) \qquad (3.1)$$

where specific gravity, SG, is calculated from Eq. (3.2)

$$SG = 141.5/(131.5 + API) \qquad (3.2)$$

and weight fraction of carbon is calculated from Eq. (3.3)

$$\%C = 100 - \%S - \%H_2 \qquad (3.3)$$

Molar flow of fuel oil combustion products, M', are found from Eqs. (3.4), (3.5) and (3.6).

$$M'_{CO_2} = \frac{W_{fo}\ \%C}{12(100)} \qquad (3.4)$$

$$M'_{H_2O} = \frac{W_{fo}\ \%H_2}{2(100)} \qquad (3.5)$$

$$M'_{SO_2} = \frac{W_{fo}\ \%\ S}{32.06(100)} \qquad (3.6)$$

where W_{fo} is mass flow of fuel oil.

Theoretical oxygen for fuel oil is calculated from Eq. (3.7).

$$M'_{O_2} = M'_{CO_2} + M'_{SO_2} + (1/2)M'_{H_2O} \qquad (3.7)$$

Molar flow of fuel gas combustion products, M", by assuming 50 percent of alkane and 50 percent of alkene in hydrocarbons having two, three, four carbons are given by Eqs. (3.8) to (3.10).

$$M''_{CO_2} = \frac{M_{fg}}{100}(\%CO_2 + \%CO + \%CH_4 + 2\%C_2 + 3\%C_3 + 4\%C_4) \qquad (3.8)$$

$$M''_{H_2O} = \frac{M_{fg}}{100}(\%H_2S + \%H_2 + 2\%CH_4 + 2.5\%C_2 + 3.5\%C_3 + 4.5\%C_4) \qquad (3.9)$$

$$M''_{SO_2} = \frac{M_{fg}}{100}(\%H_2S) \qquad (3.10)$$

Theoretical oxygen for fuel gas is calculated from Eq. (3.11).

$$M''_{O_2} = M''_{SO_2} + (1/2)M''_{H_2O} + [M''_{CO_2} - (M_{fg}/100)(\%CO_2 + (1/2)\%CO)] \qquad (3.11)$$

Total theoretical oxygen, $M^t_{O_2}$, from air is found from Eq. (3.12)

$$M^t_{O_2} = M'_{O_2} + M''_{O_2} - (M_{fg}/100)\%O_2 \qquad (3.12)$$

Then air flowrate, M_a, is found from Eq. (3.13).

$$M_a = (1 + \frac{\%\ \text{Excess}}{100})M^t_{O_2}/0.21 \qquad (3.13)$$

Molar flow of flue gas, M_G, is found by adding molar flow of each product and inerts.

Carbon dioxide flow is found by adding equations (3.4) and (3.8).

$$M_{CO_2} = M'_{CO_2} + M''_{CO_2} \tag{3.14}$$

Sulfur dioxide flow is found by adding equations (3.6) and (3.10).

$$M_{SO_2} = M'_{SO_2} + M''_{SO_2} \tag{3.15}$$

Water vapor flow is found by adding equations (3.5), (3.9) and steam flow

$$M_{H_2O} = M'_{H_2O} + M''_{H_2O} + (W_{a\,s}/18) \tag{3.16}$$

where $W_{a\ s} = W_{fo}\ 0.3056$ (3.17)

Nitrogen flow is found from flue gas and air

$$M_{N_2} = 0.79M_a + (M_{fg}/100)\%N_2 \tag{3.18}$$

Oxygen flow is found from excess air.

$$M_{O_2} = \frac{\%\ \text{Excess}}{100} M^t_{O_2} \tag{3.19}$$

$$M_G = M_{CO_2} + M_{SO_2} + M_{H_2O} + M_{N_2} + M_{O_2} \tag{3.20}$$

Dividing each equation from (3.14) to (3.18) by equation (3.20) results in the mole fraction of each component in flue gas which are respectively m_{CO_2}, m_{SO_2}, m_{H_2O}, m_{N_2}, m_{O_2}. The molecular weight of flue gas, MW_G, is

$$MW_G = 44\ m_{CO_2} + 64\ m_{SO_2} + 18\ m_{H_2O} + 28\ m_{N_2} + 32\ m_{O_2} \tag{3.21}$$

2. Energy Balance in the Combustion Chamber

Energy balance is needed to calculate the heat input to the furnace and the adiabatic flame temperature. Heat input is defined as the sum of the sensible heat of inputs and heat of combustion of fuel.

Sensible heat of inputs, Q_{sh}, can be written as sum of inlet enthalpy, H, of each input.

$$Q_{sh} = W_{fo}H_{fo} + M_{fg}H_{fg} + W_{as}H_{as} + M_aH_a \qquad (3.21)$$

where the inlet enthalpy, H_{fo}, for fuel oil is found from Eq. (3.22)

$$H_{fo} = \int_{298}^{T_{i,fo}} Cp_{fo}\, dT \qquad (3.22)$$

Specific heat, Cp_{fo}, in equation (3.22) can be evaluated by substituting the values of fuel oil into the equation (3.23) which gives specific heat of petroleum fractions [22] as function of specific gravity, SG, and characterization factor, K.

$$Cp_{p\ f,\ell} = [0.6811 - 0.308SG + T(0.000815 - 0.000306SG)][0.055K + 0.35] \qquad (3.23)$$

where

$$K = Y\nu^{0.015} + z \qquad (3.24)$$

$$Y = -91.90768API + 9.14945API^2 - 0.39620API^3 + 0.00632API^4 + 347.56742$$

$$z = 100.73420API - 10.04215API^2 + 0.43579API^3 - 0.00697API^4 - 369.64072$$

Equation (3.24) is found by curve fitting as explained in Appendix A.2.

The inlet enthalpy, H_{as}, for steam is calculated from Eq. (3.25).

$$H_{as} = [(0.00048P + 0.46003T) - 0.35437P + 1059.76347]0.5559 \tag{3.25}$$

Equation (3.25) is also found by curve fitting as explained in Appendix A.1. Here temperature is in °F and pressure is in psi, the result is converted from Btu/lb to kcal/kg by multiplying with 0.55519.

The inlet enthalpy, H_a, for air is calculated from Eq. (3.26) [23] as;

$$H_a = \int_{298}^{T_{i,a}} (0.6173 + 4.697\text{x}10^{-4}T + 0.1147\text{x}10^{-5}T^2 - 4.696\text{x}10^{-10}T^4)dT \tag{3.26}$$

The inlet enthalpy, $H_{f\,g}$, for fuel gas is found from Eq. (3.27)

$$H_{f\,g} = \sum_{n=1}^{11} \int_{298}^{T_{i,fg}} m_n C_{p_n}\, dT \tag{3.27}$$

where n in Eq. (3.27) refers to each compound in fuel gas as given in Section 3.A.1 and C_p value for each is found from literature [23].

Heat of combustion, Q_{ch}, for fuel is the sum of heat of combustion of fuel oil [21] and fuel gas [24].

$$Q_{ch} = W_{fo}(12400 - 2100SG_{fo}^2) + 8.905V_{fg} \sum_{n=1}^{11} m_n \Delta H_{r_n} \tag{3.28}$$

where ΔH_{r_n} is the heat of combustion reaction for each compound in fuel gas. Then total heat input to the system, Q_{tt}, is sum of Eqs. (3.21) and (3.27).

$$Q_{tt} = Q_{sh} + Q_{ch} \tag{3.29}$$

When Q_{tt} is known, adiabatic flame temperature can be found by assuming that all entering energy is available to raise the temperature of the products and the products leave at the temperature of reactions.

III.B MODELLING OF THE SECTIONS

The explanation of how the modelling equations used in computer program are derived for each section is given in this part.

Each section is divided into stages which correspond to one tube row that is assumed to have uniform gas temperature distribution which varies only along the height of the furnace at the outside of the tubes. The tubes are assumed to have constant wall temperatures and negligible wall resistances. The fluid in the tubes flows horizontally, which is assumed to have uniform temperature distribution that varies only along the length of the tube, and because of symmetry only one stream is analyzed.

The radiant heat transfer is assumed to be between flame and tube banks and that gas radiation is negligible in radiation section.

1. Convection Section

There are six rows, each row containing four tubes, two for each stream. The flue gas flow is perpendicular to the staggered tube bank.

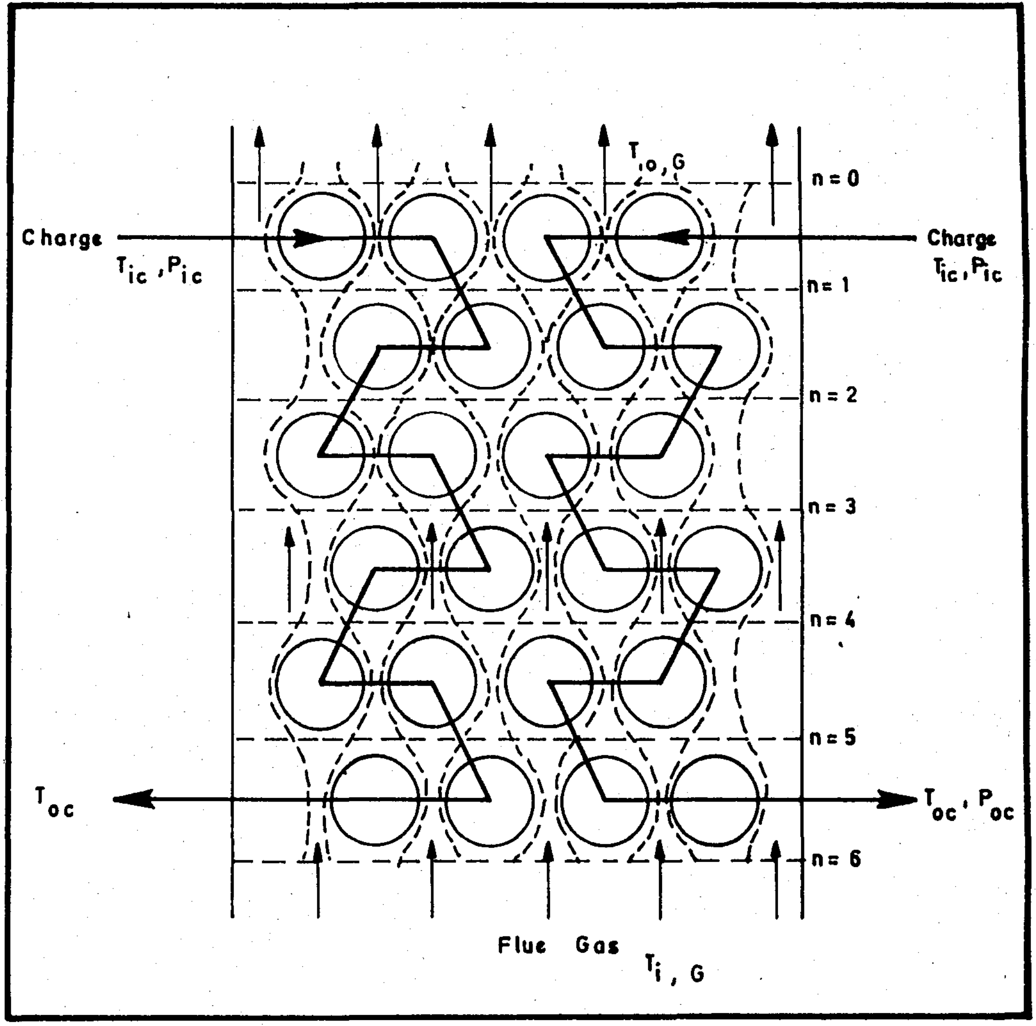

Figure 3.2 Schematic Diagram of Convection Section

a. Temperature Distribution

Although convective heat transfer is the primary mode of heat transmission in this section, radiative effects also contribute because of radiation from the hot flue gases and reradiation from the walls of the convection section.

In order to increase transfer rates per unit length of tubing, tubes have fins, extended-surface, in the form of studs. With all of the extended-surface types, radiant transfer to the convection tubes is so small that can be neglected [1].

Energy balance at steady-state is applied to flue gas and charge in each stage in order to find temperatures of charge outlet and flue gas inlet [25].

Energy balance on flue gas gives:

$$Q_G = M_G \int_{T_G^{n-1}}^{T_G^n} Cp_G \, dT = \text{Change in heat content of flue gas} \tag{3.30a}$$

$$Q_G = 4A_t h_o(\overline{T}_G - T_s) = \text{heat absorbed by tubes} \tag{3.30b}$$

where Cp_G, the specific heat of flue gas, is found from Eq. (3.31).

$$Cp_G = \sum_{j=1}^{5} m_j Cp_{G,j} \tag{3.31}$$

$Cp_{G,j}$ values are for CO_2, H_2O, SO_2, N_2 and O_2 [23] which have the form as given in Eq. (3.32).

$$Cp_{G,j} = A + BT + CT^2 + DT^3 \tag{3.32}$$

And average gas temperature, $\overline{T}_G$, is found from Eq. (3.33).

$$\overline{T}_G = \frac{1}{2}(T_G^n - T_G^{n-1}) \tag{3.33}$$

Energy balance applied on the tube wall gives heat absorbed by convection from gas is equal to the heat removed by convection to charge.

$$A_t h_o(\overline{T}_G - T_s) = \pi D_i L_t h_i(T_s - \overline{T}_c) \tag{3.34}$$

where average charge temperature is given by Eq. (3.35).

$$\bar{T}_c = \frac{1}{2}(T_{i,c} + T_{o,c}) \tag{3.35}$$

The charge outlet temperature $T_{o,c}$ is evaluated from Eq. (3.36).

$$T_{o,c} = T_{i,c} + \frac{Q_G}{2W_c C_{p_{c,\ell}}} \tag{3.36}$$

And specific heat of charge $C_{p_{c,\ell}}$ is calculated from Eq. (3.23).

Heat transfer coefficients h_i and h_o are found using empirical equations given in literature since no experimental work was possible.

The heat transfer coefficient for fully developed turbulent flow inside tubes with $1.0 \leq Pr \leq 20$ [20] is given as;

$$h_i = 0.0155 Pr^{0.5} Re^{0.83} (k_{c,\ell}/D_i). \tag{3.37}$$

The properties of charge used for the calculation of h_i are as follows: Thermal conductivity [27] $k_{c\ell}$ is obtained by using Eq. (3.38)

$$k_{c,\ell} = \frac{0.06775[1 - 0.0003(1.8(T - 273))]}{SG}(1.488) \tag{3.38}$$

Density [27], $\rho_{c,\ell}$, is calculated from Eq. (3.39).

$$\rho_{c,\ell} = SG_c(\omega/\omega_1) \tag{3.39}$$

where expansion factor, ω, is given as;

$$\omega = 0.1745 - 0.0838(T/T_{critical}) \tag{3.40}$$

and [28]

$$T_{critical} = \frac{[180 + 1.75a - 0.0008a^2] - 32}{1.8} + 273 \tag{3.41}$$

where

$$a = [(K \cdot SG)^3 + 100]SG \tag{3.42}$$

Specific heat is evaluated from Eq. (3.23). Kinematic viscosity [29] is evaluated from the following set of equations.

$$\log_{10}\log_{10}Z = A + B\log_{10}T \tag{3.43}$$

where

$$Z = \nu + 0.7 + C - D + E - F + G - H \tag{3.44a}$$

$$C = \exp(-1.4883 - 2.65868\nu) \tag{3.44b}$$

$$D = \exp(-0.00381308 - 12.5645\nu) \tag{3.44c}$$

$$E = \exp(5.46491 - 37.62898\nu) \tag{3.44d}$$

$$F = \exp(13.0458 - 74.6851\nu) \tag{3.44e}$$

$$G = \exp(37.4619 - 192.643\nu) \tag{3.44f}$$

$$H = \exp(80.4945 - 400.468\nu) \tag{3.44g}$$

A and B are constants and evaluated from kinematic viscosities at two known points.

$$B = \frac{\log\log Z_1 - \log\log Z_2}{\log T_2 - \log T_1} \tag{3.45}$$

$$A = B\log T_1 + \log\log Z_1 \tag{3.46}$$

Knowing A and B, Z can be evaluated at given temperature then using Z kinematic viscosity ν is obtained.

The heat transfer coefficient on the outside is estimated from the equations developed by Monrad [30] for flue gas flowing perpendicular to a bank of tubes, which is given as;

$$h_o = (1 + \eta)(h_c + h_{rG})4.88 \tag{3.47}$$

Pure convection coefficient h_c is given by Eq. (3.48).

$$h_c = \frac{1.6G_G^{0.667}T^{0.3}}{D_o^{0.33}} \tag{3.48}$$

Here T is in °F, D_o is in inches, and G_G is in lb/ft²-sec.

$$G_G = \frac{S_T W_G 2.2046/3600}{[S_T - D_o][A_{Base} - 4D_o L_t]} \tag{3.49}$$

S_T is staggering distance and units of length and area are ft and ft² respectively.

Coefficient of heat transfer from the gas by radiation is given by Eq. (3.50).

$$h_{rG} = 0.0025\ T - 0.5 \tag{3.50}$$

T is average gas temperature in °F.

Reradiation from walls of the convection section usually ranges from 0.06 to 0.15 of the sum of the pure convection and the radiation coefficients [1]

$$\eta = \frac{h_{rb} \cdot A_{wall}}{(h_c + h_{rG} + h_{rb})(A_{t,tt} + A_{wall})} \tag{3.51}$$

where heat transfer coefficient due to reflection from walls, h_{rb}, is given as;

$$h_{rb} = 0.006(T/100)^3 \tag{3.52}$$

Here temperature is given in degrees Rankine. The overall coefficient is given by Eq. (3.47).

b. Pressure Drop

Since nearly half of the charge vaporizes in the furnace the pressure drop needs to be calculated in order to estimate where the two phase flow starts. The following relationship [31] gives the pressure drop in the tubes.

$$\Delta P = \frac{2L_e G_c^2 f}{D_i \rho_c} \times 7.61\text{x}10^{-13} \qquad (3.53)$$

where $7.61\text{x}10^{-13}$ is the conversion factor from kg/m.hr^2 to atmospheres and f is the fanning friction factor. An equation for the fanning friction factor in terms of Reynolds number is

$$1/\sqrt{4f} = 0.87 \ln Re\sqrt{4f} - 0.8 \qquad (3.54)$$

for $30\ 000 \leq Re \leq 1\ 000\ 000$.

In this correlation, L_e is the total hydraulic length and is based on the sum of the actual tube length plus the equivalent length of return fittings, bends, etc.

2. Radiation Section

There are 23 stages (rows) with 2 tubes, one for each stream on the two sides, plus one row at the ceiling with six tubes three for each stream.

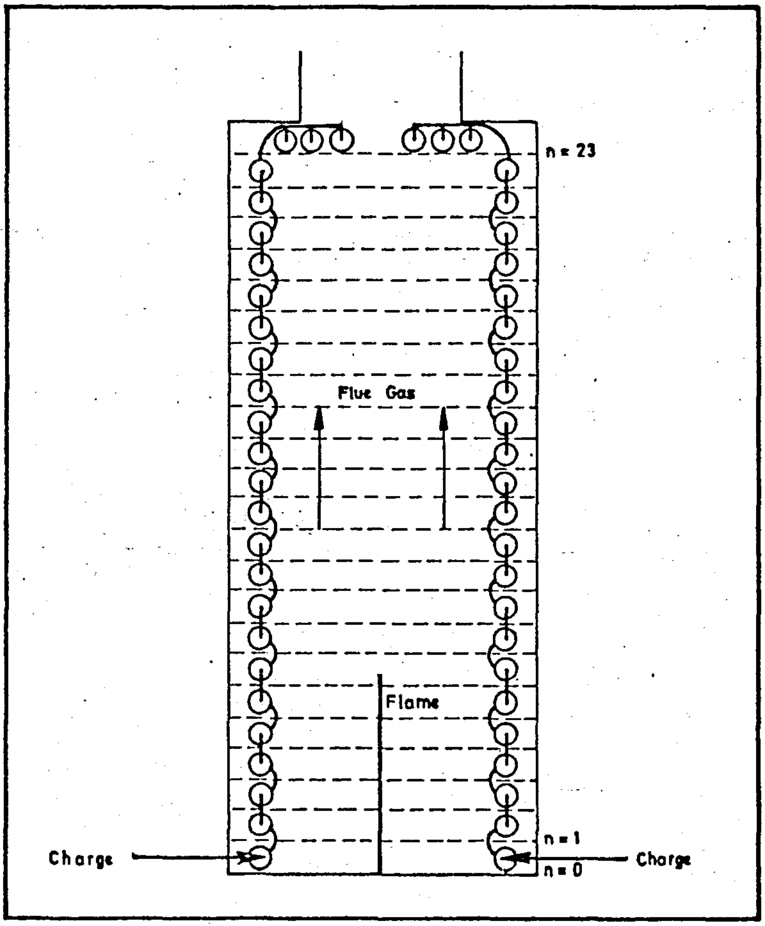

Figure 3.3 Schematic Diagram of Radiation Section

There are 14 burners placed at the centerline of the floor with equal spacing in between therefore the flame is assumed to be planar parallel to the walls, and have the same length, and height approximately 0.24 times the wall height. The radiation from flame is assumed to be diffuse and surfaces are gray.

It is also assumed that there is no heat loss in charge during transportation from convection section to radiation section.

Since, there are two different flow for charge which are single phase and two phase flows and two different radiation angle factors for tubes which are placed on side walls and ceiling of radiation section, the analysis is carried in three parts all at steady-state conditions.

a. Liquid Phase Flow in Tubes on the Walls

Although radiative transfer is predicted to be the primary mode of heat transmission in this section, convective heat transfer also contributes because of flowing gas [6,10,30,32].

Adiabatic flame temperature needed in radiation heat transfer is found as explained in Section III.A.2. Then energy balance and pressure drop calculations are made for each stage.

Heat released by combustion gas is found from Eq. (3.30a) by changing integration limits from $T_G^n \rightarrow T_G^{n-1}$ to $T_G^{n-1} \rightarrow T_G^n$ because $T_G^{n-1} > T_G^n$. The specific heat of combustion gas has same formulation as in convection section, given by Eq. (3.31). The heat given by combustion gas is equal to the two times the heat absorbed by charge flowing in each tube that is given as;

$$Q_G/2 = W_c\ Cp_{c,\ell}(T_{o,c} - T_{i,c}) \tag{3.55}$$

Specific heat of charge is calculated from Eq. (3.23).

Energy balance applied at the tube surface gives energy absorbed by radiation and convection.

$$Q_G/2 = \sigma(A_{t,r}/2)\phi(T_f^4 - T_s^4) + A_{t,r}h_o(\bar{T}_G - T_s) \tag{3.56}$$

equals to heat removed by convection to charge

$$Q_G/2 = h_i\pi D_{i,r}L_t(T_s - \bar{T}_c) \tag{3.57}$$

The inside heat transfer coefficient h_i in Eq. (3.57) is evaluated from Eqs. (3.37) to (3.46) by using conditions of this section.

The outside heat transfer coefficient h_o in Eq. (3.56) which includes pure convection, radiation from gas and reradiation from walls is evaluated from Eqs. (3.47) to (3.52) by using conditions of this section. Since the configuration of tubes is different in this section Eq. (3.49) cannot be used to evaluate G_G instead of Eq. (3.58) is used.

$$G_{G,r} = W_G/A_{Base,r} \tag{3.58}$$

Radiation exchange factor ϕ in Eq. (3.56) is given as;

$$\phi = \varepsilon_f F_{A_f-A_s} \tag{3.59}$$

where emissivity of flame ε_f is the ratio of the heat actually transmitted from flame to the colder surface to the heat which would have been transmitted had the flame and colder surface been perfect radiators [10,30].

$$\varepsilon_f = f(PL, t_G, t_s) \tag{3.60}$$

where

t_s = tube surface temperature, °F
t_G = gas temperature at bridge wall, °F
$PL = (P_{CO_2} + P_{H_2O})L$, atm-ft
L = mean length of radiant beam in combustion chamber [10,30]; for this case it is equal to 14.7999 ft

Since possible changes that can happen in the furnace in PL and t_s does not affect ε_f much, Equation (3.60) can be approximated to

Equation (3.61) which is obtained by the author by curve fitting

$$\varepsilon_f = f(t_g) = -9.72222\times10^{-5}(t_g - 2000) + 0.458 \qquad (3.61)$$

$F_{A_f - A_s}$ in Eq. (3.59) is the radiation angle factor for diffuse interchange between flame and stage. Assuming radiosity is uniform over A_i it can be written [33] as

$$F_{A_i - A_j} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\beta_i \cos\beta_j \, dA_j \, dA_i}{\pi r^2} \qquad (3.62)$$

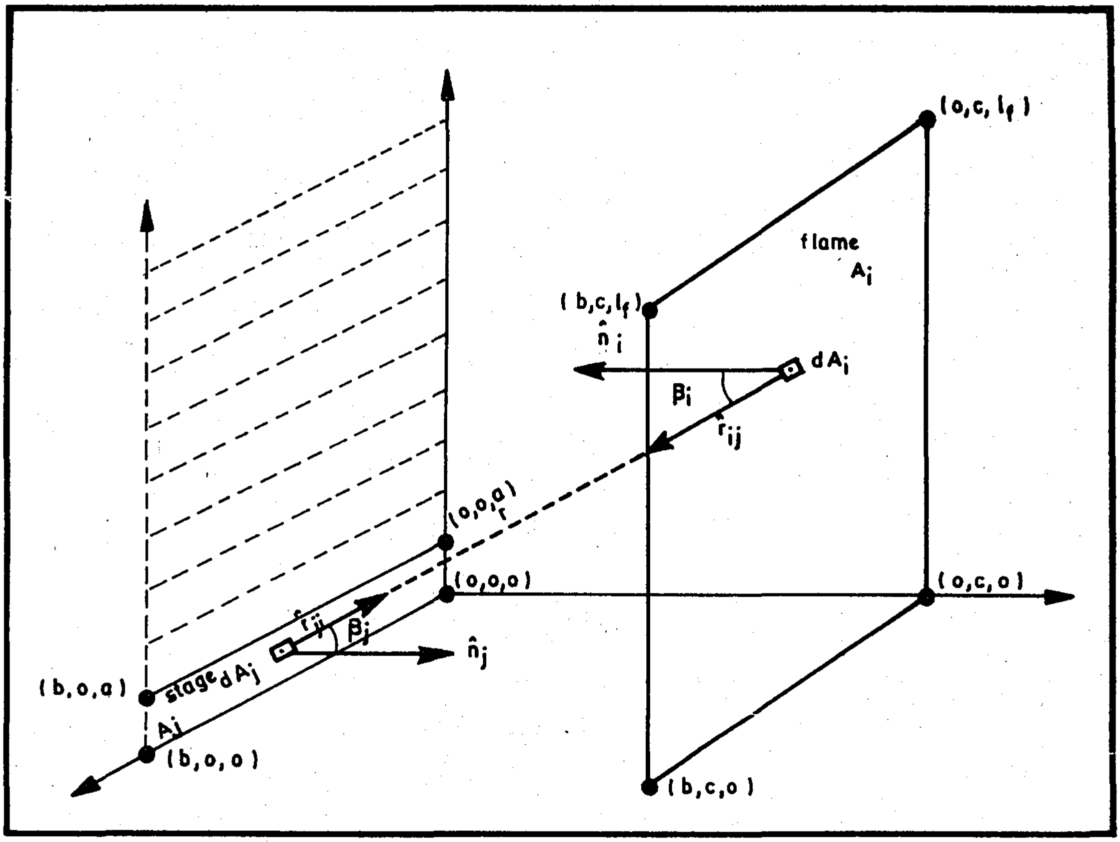

Figure 3.4 Configuration for Intercharge Between Flame and Stage

In order to use Eq. (3.62) in computation it is necessary to evaluate $\cos\beta_i$, $\cos\beta_j$, r, dA_j and dA_i in terms of coordinates. They are [33]

$$\hat{n} = \hat{i}\ell + \hat{j}m + \hat{k}n \tag{3.63}$$

$$r^2 = (x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2 \tag{3.64}$$

$$\cos\beta_i = \hat{n}_i \cdot \hat{r}_{ij} = \frac{1}{r}[\ell_i(x_j - x_i) + m_i(y_j - y_i) + n_i(z_j - z_i)] \tag{3.65}$$

$$\cos\beta_j = \hat{n}_j \cdot \hat{r}_{ji} = \frac{1}{r}[\ell_j(x_i - x_j) + m_j(y_i - y_j) + n_j(z_i - z_j)] \tag{3.66}$$

where $\hat{r}$ is the unit vector that lies along the connection line of the surfaces.

For this configuration where A_j moves along the z-axis as the stage number increases $F_{A_i - A_j}$ can be obtained as follows:

$\hat{n}$ can be evaluated from the cosine of angles between the unit vectors and coordinate axises

$$\ell_i = 0 \qquad m_i = -1 \qquad n_i = 0 \qquad \therefore\ \hat{n}_i = -\hat{j} \tag{3.67}$$

$$\ell_j = 0 \qquad m_j = 1 \qquad n_j = 0 \qquad \therefore\ \hat{n}_j = \hat{j} \tag{3.68}$$

Since $y_j = 0$ the square of the distance between two surfaces is

$$r^2 = (x_i - x_j)^2 + y_i^2 + (z_i - z_j)^2 \tag{3.69}$$

Directional cosines are

$$\cos\beta_i = \frac{1}{r}\, y_i = \cos\beta_j \tag{3.70}$$

Areas are $A_i = bL_f$

$$\int_{A_i} dA_i = \int_0^b dx_i \int_0^{L_f} dz_i \tag{3.71}$$

$$\int_{A_j} dA_j = \int_0^b dx_j \int_{(s-1)a}^{sa} dz_i \qquad s = 1,\ldots,23 \tag{3.72}$$

Substituting Eqs. (3.69), (3.70), (3.71) and (3.72) into Eq. (3.62) angle factor is found to be

$$F_{A_i-A_j} = \frac{1}{\pi b L_f} \int_0^b \int_0^{L_f} \int_0^b \int_{(s-1)a}^{sa} \frac{y_i^2\, dz_j dx_j dz_i dx_i}{[(x_i-x_j)^2+y_i^2+(z_i-z_j)^2]^2} \tag{3.73}$$

The evaluation of integral (3.73) is shown in Appendix B, the result is given by Eq. (3.74).

$$\begin{aligned}
F_{A_f-A_s} = \frac{c^2}{\pi b L_f}\{ &\frac{1}{c}[(L_f-sa)\tan^{-1}((L_f-sa)/c) - sa\tan^{-1}(sa/c) \\
&+ (s-1)a\tan^{-1}((s-1)a/c) - (L_f-(s-1)a)\tan^{-1}((L_f-(s-1)a)/c)] \\
&- (\sqrt{b^2+c^2}/c^2)[(L_f-sa)\tan^{-1}((L_f-sa)/\sqrt{b^2+c^2}) - sa\tan^{-1}(sa/\sqrt{b^2+c^2}) \\
&+ (s-1)a\tan^{-1}((s-1)a/\sqrt{b^2+c^2}) - (L_f-(s-1)a)\tan^{-1}((L_f-(s-1)a)/\sqrt{b^2+c^2})] \\
&-(b^2/c^2)[\sqrt{c^2+(L_f-sa)^2}\tan^{-1}(b/\sqrt{c^2+(L_f-sa)^2}) \\
&- \sqrt{c^2+s^2a^2}\tan^{-1}(b/\sqrt{c^2+s^2a^2}) + \sqrt{c^2+(s-1)^2a^2}\tan^{-1}(b/\sqrt{c^2+(s-1)^2a^2}) \\
&- \sqrt{c^2+(L_f-(s-1)a)^2}\tan^{-1}(b/\sqrt{c^2+(L_f-(s-1)a)^2})] \\
&+ \frac{1}{2}[\ln((c^2+(L_f-sa)^2+b^2)/(c^2+(L_f-sa)^2)) - \ln((c^2+s^2a^2+b^2)/(c^2+s^2a^2)) \\
&+ \ln((c^2+(s-1)^2a^2+b^2)/(c^2+(s-1)^2a^2)) \\
&- \ln((c^2+(L_f-(s-1)a)^2+b^2)/(c^2+(L_f-(s-1)a)^2))]\}
\end{aligned} \tag{3.74}$$

After finding ΔP from Eq. (3.53) and (3.54) for tube flow, boiling point at outlet pressure is found from Eq. (3.75) which is derived by curve fitting as explained in Appendix A.5.

$$T_B \text{ at } P_{o,c} = [(T_B - b)/\ a - 32\ ]/1.8 + 273 \qquad (3.75)$$

where

$$a = 0.12906 \log_{10}(1/P_{o,c}) + 0.99316$$

$$b = 106.46313 \log(1/P_{o,c}) + 4.29520$$

b. Liquid-Gas Phase Flow in Tubes on the Walls

When the charge outlet temperature from tube is approximately equal to the charge boiling temperature at charge outlet pressure from tube, two phase flow is assumed to start.

The modelling equations on the gas side are the same as in part a which are Eqs. (3.30a), (3.31), (3.56), (3.58), (3.59), (3.61) and (3.74).

Energy balance on the charge gives the fraction that is vaporized since charge temperature is assumed to be constant during vaporization.

$$Q_G/2 = H_{v,c} \times W_c \qquad (3.76)$$

where heat of vaporization for petroleum fractions [34] is given by Eq. (3.77).

$$H_v = (T_B/MW)(8.75 + 4.571 \log_{10}T_B) \qquad (3.77)$$

and

$$MW = be^{aK} \tag{3.78}$$

$$a \;= 33.14991\cos(API/120) + 0.00107API^2 - 32.37044$$

$$b \;= 0.20814 + 1\text{x}10^{-5}API(-2391.69992 + 150.66076API$$

$$- 4.37442API^2 + 0.05865API^3 - 2.9\text{x}10^{-4}API^4)$$

Equation for molecular weight, MW, is derived by curve fitting as described in Appendix A.3.

Energy balance applied on the tube surface, Eq. (3.56), gives heat absorbed by radiation and convection equals to heat removed by charge.

$$Q_G/2 = h_{tp}\,\pi D_{i,r} L_t (T_s - \bar{T}_c) \tag{3.79}$$

Two phase flow convective heat transfer coefficient h_{tp} can be evaluated at the end of a series of steps as to be explained in the following paragraphs [35]. Since it depends on the flow pattern of the fluid, after finding void fraction α and superficial velocities the flow pattern is determined.

$$\alpha = \frac{1}{1 + ((1-x)/x))\rho_{c,g}/\rho_{c,\ell})(u_{c,g}/u_{c,\ell})} \tag{3.80}$$

Here the slip ratio $u_{c,g}/u_{c,\ell}$ is assumed to be unity, and $\rho_{c,g}$ is found from Eq. (3.81).

$$\rho_{c,g} = \frac{P_c}{Z\,R\,T_c} \tag{3.81}$$

where for $P_c/P_{critical} > 2$ [22] is given as;

$$Z = 1.0 - (0.24 - 0.14(T_c/T_{critical}))(8 - (P_c/P_{critical})) \tag{3.82}$$

for $P_c/P_{critical} \leq 2$ [32] is given as;

$$Z = 1.0 - [0.73(T_c/T_{critical})^{-3} - 0.18](P_c/P_{critical}) \tag{3.83}$$

$T_{critical}$ is found from Eqs. (3.41) and (3.42) and $P_{critical}$ is found from Eqs. (3.84) derived by curve fitting as described in Appendix A.5 which is

$$P_{critical} = b\ T^a_{critical}/\ 14.696 \tag{3.84}$$

$$a = 0.37036x10^{-5}T_B^2 + 4.09629$$

$$b = \exp(-3x10^{-5}T_B^2 - 20.13179)$$

The superficial velocities are calculated from Eqs. (3.85) and (3.86).

$$v_{c,g} = \frac{x\ W_c}{\rho_{c,g}\ \pi(D_{i,r}/2)^2\ 3600} \tag{3.85}$$

$$v_{c,\ell} = v_{c,g}((1 - \alpha)/\alpha) \tag{3.86}$$

The parameters F and Y are also needed to be calculated and these are given by Eq. (3.87).

$$F = (\rho_{c,g}/\rho_a)^{0.333}((\rho_{c,\ell}/\rho_w)(\gamma_w/\gamma_c))^{0.25}(\mu_{c,g}/\mu_a)^{0.2} \tag{3.87}$$

$$Y = (\mu_{c,\ell}/\mu_w)^{0.2}((\rho_{c,\ell}/\rho_w)(\gamma_w/\gamma_{c,\ell}))^{0.25}$$

subscript a, w refer to air and water at atmospheric pressure and ambient temperature.

Now the flow pattern can be determined. For $v_{c,\ell} \leq 0.1Y$ the flow is annular mist if $v_{c,g} > 15F$ otherwise strafied or wave flow. For $4Y \geq v_{c,\ell} > 0.1Y$ the flow is annular if $v_{c,g} > F[0.001 + (v_{c,\ell} - 0.4)0.057457]$ otherwise bubble or slug flow. For $v_{c,\ell} > 4Y$ the flow is dispersed bubble or annular as shown by lines in Figure 3.5.

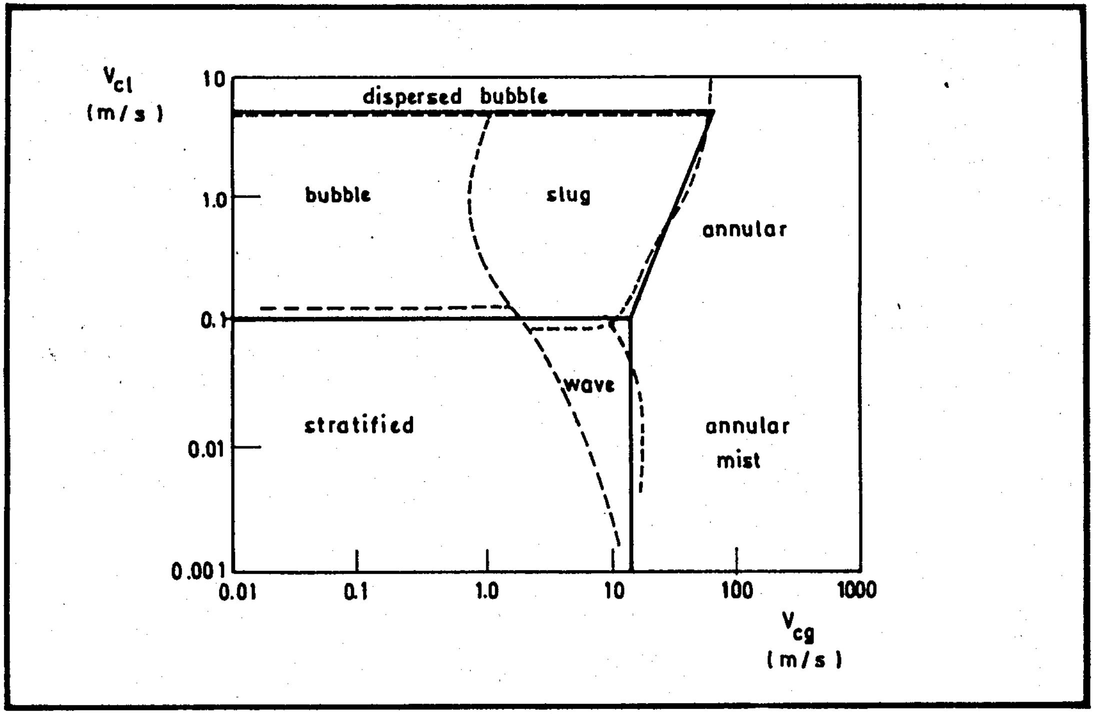

Figure 3.5 Flow Pattern Map for Horizontal Flow [35]

This map is prepared by Mandhane et al for air-water system shown by dashed lines in Figure 3.5. For fluids other than air-water transition lines given by $v_{c,\ell} = f(v_{c,g})$ or $v_{c,g} = f(v_{c,\ell})$ must be modified to

$$v_{c,\ell} = X_1 f(v_{c,g}) \qquad \text{or} \qquad v_{c,g} = X_2 f(v_{c,\ell})$$

where X is a parameter represented either by F or Y of Eq. (3.87).

If the top part of the tube wall is wet as in our case that means the flow pattern is dispersed bubble, annular or annular mist, then Chen correlation is used to find two phase flow convective heat transfer coefficient.

In Chen correlation first the Martinelli parameter is found that is given as;

$$X_{tt} = ((1 - x)/x)^{0.9}(\rho_{c,g}/\rho_{c,\ell})^{0.5}(\mu_{c,\ell}/\mu_{c,g})^{0.1} \tag{3.88}$$

convective heat transfer correction factor, F_c, is derived by curve fitting as described in Appendix A.7.

$$F_c = 0.862888 + \frac{1.426638}{X_{tt}} + \frac{0.074524}{X_{tt}^2} - \frac{0.011958}{X_{tt}^3} \tag{3.89}$$

$$Re_{tp} = F_c^{1.25} \cdot Re_\ell = \frac{G_c(1 - x)D}{\mu_{c,\ell}} F_c^{1.25}$$

Based on Dittus-Boelter relationship for liquid flowing alone in a heated conduit Chen proposed for a convective component of h_{tp} which is h_{mac} and given as;

$$h_{mac} = 0.023\, Re_{tp}^{0.8}(Pr_\ell)^{0.4}(k_{c,\ell}/D_{i,r}) \tag{3.90}$$

By knowing Re_{tp} nucleate boiling suppression factor, S_c, can be found from equation derived by curve fitting as explained in Appendix A.8.

$$S_c = -0.4669855 + 17.6252375[Re_{tp}^{-0.265}] \qquad (3.91)$$

Δ saturation values are evaluated by Eqs. (3.92) and (3.93).

$$\Delta T_{sat} = T_w - T_B \text{ at } P_c \qquad (3.92)$$

$$\Delta P_{sat} = P_{\text{at } T_w} - P_{\text{at } T_B} \qquad (3.93)$$

Based on Forster and Zuber relationship for nucleate pool boiling Chen proposed for microconvective heat transfer, h_{mic}, and it is given as;

$$h_{mic} = 0.00122[k_{c,\ell}^{0.79} Cp_{c,}^{0.45} \rho_{c,\ell}^{0.49} / \gamma_{c,\ell}^{0.5} \mu_{c,\ell}^{0.29} H_{vc}^{0.24} \rho_{c,g}^{0.24}] \Delta T_{sat}^{0.24} \Delta P_{sat}^{0.75} S_c \qquad (3.94)$$

Since units of h_{mic} is w/m²K it is multiplied by 0.859845227 to convert to kcal/m²-K.hr. The units of physical properties are $k_{c,\ell}$(w/mK), $Cp_{c,\ell}$(J/kg-K), ρ(kg/m³), γ(N/m), μ(kg/m-s) and H_{v_c} (J/kg).

Two phase coefficient is calculated by adding h_{mac} and h_{mic}.

$$h_{tp} = h_{mac} + h_{mic} \qquad (3.95)$$

If the top part of the tube wall is dry or periodically wet that means flow pattern is bubble, slug, stratified or wave, h_{tp} is found by Eq. (3.96).

$$h_{tp} = \frac{\theta}{\pi} h_g + (h_\ell + h_n)(1 - \frac{\theta}{\pi}) \qquad (3.96)$$

Here h_g and h_ℓ can be calculated by assuming that phases flowing alone in tubes whose diameters are appropriate hydraulic mean diameters.

h_ℓ is found from Eqs. (3.37) to (3.42) by using $D_{h,\ell}$ instead of D_i which is calculated from Eq. (3.97)

$$D_{h,\ell} = 2\sqrt{\pi(D_{i,r}/2)^2(1-x)/\pi} \tag{3.97}$$

and h_g is calculated by using Eq. (3.98)

$$h_g = 0.023\, Re_g^{0.8} Pr_g^{0.4} (k_{c,g}/D_{h,g}) \tag{3.98}$$

where

$$D_{h,g} = 2\sqrt{\pi(D_{i,r}/2)^2 x/\pi} \tag{3.99}$$

Thermal conductivity of gas phase of petroleum fractions is derived by curve fitting as explained in Appendix A.4, the result is given by Eq. (3.100).

$$k_{c,g} = \{a[(T - 273)1.8 + 32] + b\}1.4888 \tag{3.100}$$

where

$$a = 3.79\text{x}10^{-7}\, MW_c + 2.6\text{x}10^{-4} MW_c^{-0.31342} - 6\text{x}10^{-5} - 1\text{x}10^{-9} MW_c^2$$

and

$$b = 0.1126 MW_c^{-0.47367} - 0.00574 \sin MW_c^{0.3} - 0.01902$$

In order to calculate S_c from Eq. (3.91) Re_{tp} is needed and it is found by using from Eq. (3.101).

$$Re_{tp} = \frac{\rho_{c,\ell} u_{c,\ell} D_{h,\ell}}{\mu_{c,\ell}} \tag{3.101}$$

Then using Eqs. (3.92) to (3.94) h_n is evaluated.

Only unknown variable left in Eq. (3.96) is θ which is the angle between tube diameter and liquid surface,

$$\theta = \frac{\alpha\ 180}{\pi} \tag{3.102}$$

Substituting the values obtained from Eqs. (3.37), (3.94), (3.98) and (3.102) into Eq. (3.96) gives the numerical value of h_{tp}.

c. Liquid-Gas Flow in Tubes on the Ceiling

The modelling equations of this section is same as in previous section with few differences. Since the fluid is separated into three tubes and pass through once mass flow of charge is one third of W_c and heat transfer to each tube ($= Q_G/6$) is one third of heat transfer used in preceeding section.

Angle factor in Eq. (3.59) is also different for this section. Here the plane of tubes is perpendicular to the plane of flame. Angle factor is found by first calculating it between flame and each tube and then taking the average of three because heat absorption by each tube is assumed to be the same.

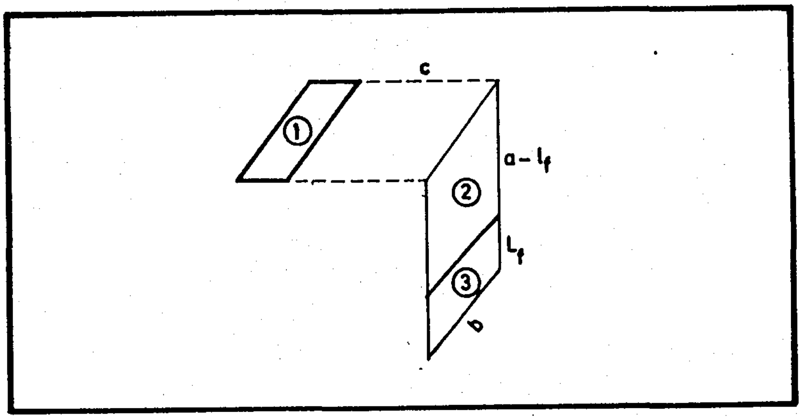

Figure 3.6 Configuration for Interchange Between Flame and Ceiling Tube.

Angle factor between plane 1, which is the tube, and plane 2 or plane 2+3 (Fig. 3.6) have the same form as they have same configuration. It is found in literature [33] which is given in Eq. (3.103) with:

$$X = \frac{\text{height}}{b} \qquad Y = \frac{c}{b} \qquad Z = X^2 + Y^2$$

$$F_{dA_1-A_2} \text{ or } F_{dA_1-(A_2+A_3)} = \frac{1}{\pi}\{\tan^{-1}(1/Y) - Y/\sqrt{Z}\ \tan^{-1}(1/\sqrt{Z}) + (Y/2)\ln[\frac{Y^2(Z+1)}{(Y^2+1)Z}]\} \tag{3.103}$$

The angle factor between tube and flame (plane 1 and plane 2) is calculated by Eq. (3.104).

$$F_{dA_1-A_3} = F_{dA_1-(A_2+A_3)} - F_{dA_1-A_2} \tag{3.104}$$

Using reciprocity rule the angle factor between flame and tube which is given by Eq. (3.106) is evaluated

$$F_{A_3-dA_1} = (dA_1/A_3)F_{dA_1-A_3} \tag{3.105}$$

$$F_{A_3-dA_1} = \frac{D_{o,r}\ c}{L_f\ \pi}\{\frac{1}{2b}\ln[\frac{(a^2+c^2+b^2)((a-L_f)^2+c^2)}{((a-L_f)^2+c^2+b^2)(a^2+c^2)}] + \frac{1}{\sqrt{(a-L_f)^2+c^2}}\tan^{-1}\frac{b}{\sqrt{(a-L_f)^2+c^2}} - \frac{1}{\sqrt{a^2+c^2}}\tan^{-1}\frac{b}{\sqrt{a^2+c^2}} \tag{3.106}$$

IV. COMPUTER PROGRAMMING

On the basis of equations of Chapter III a computer program is developed for predicting the heat transfer in the furnace. The aim is to study the effect of input parameters on the output conditions such as temperature and vapor fraction.

This chapter is composed of two parts, in the first the algorithm for each section of the furnace is given and in the second the main and the subprograms are explained.

IV.A ALGORITHM OF THE PROGRAM

The procedure used in programming is iterative, trial and error calculation.

Each section is divided into the stages equaling to the number of rows present. Because of symmetry only one stream is analyzed.

1. Convection Section

The flue gas temperature at the stack entrance, the charge inlet temperature and pressure are the knowns for this section. Therefore calculation of the temperature distribution and the pressure drop starts from the last row of tubes where the charge enters the furnace as shown in Figure 2.2.

This section is divided into six stages composed of four tubes, as seen in Figure 3.2, all having the same procedure in calculations.

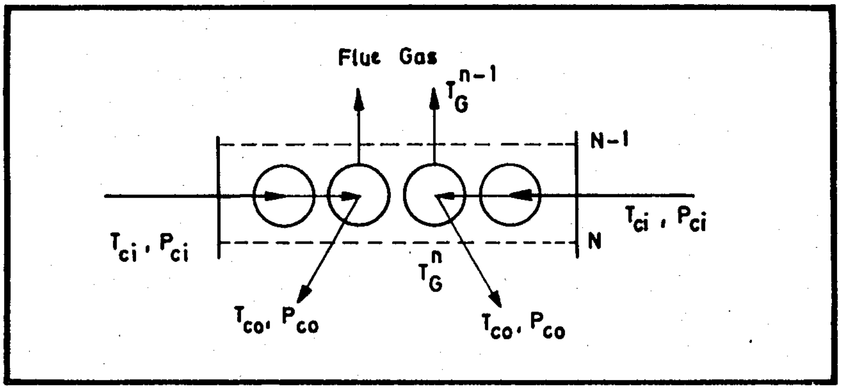

Figure 4.1 Schematic Diagram of a Stage in Convection Section

Flue gas temperature at the stage inlet is assumed to be delta amount greater than outlet temperature which is known. Delta is specified initially and increases at each stage by an increasing amount. Then heat given by gas is calculated by Eq. (3.30a).

Since heat taken by charge in each tube is one forth of heat given by gas charge outlet temperature is found from

$$T_{c_o} = T_{c_i} + \frac{Q_G}{4M_c C p_{c,\ell}} \tag{4.1}$$

After evaluating inside heat transfer coefficient from Eq. (3.37), tube surface temperature is calculated

$$T_s = \bar{T}_c + \frac{Q_G}{4\pi D_i L_t h_i} \tag{4.2}$$

Pressure drop in each tube is found by Eq. (3.53). Outside heat transfer coefficient is found from Eq. (3.47) and a new gas temperature is calculated from

$$T_G = 2T_s - T_G^{n-1} + \frac{Q_G}{2A_t h_o} \tag{4.3}$$

This new gas temperature is compared with the assumed gas temperature. If their difference is less than or equal to a specified amount, for example one degree K, the variables at the stage outlet is found. These pressure and temperature values are the inlet conditions of the next stage.

The iteration is completed at the end of sixth stage.

2. Radiation Section

The charge inlet conditions to the radiation section are the outlet temperature and pressure from convection section. The combustion gas inlet temperature is not known; therefore it is assumed equal to the adiabatic flame temperature because it is the highest possible temperature that combustion gas attain.

This section is divided into 23 single and/or two phase stages plus a ceiling stage as shown in Figure 3.3.

First single phase temperature distribution and pressure drop for tube flow is calculated using Eqs. (3.30a), (4.1), (3.37), (4.2), (3.53), (3.47) and a new gas temperature is found from Eq. (4.4).

$$T_G = 2T_s - T_G^{n-1} + \frac{Q_G}{A_t h_o} - \frac{\sigma\phi(T_F^4 - T_s^4)}{h_o} \qquad (4.4)$$

This new gas temperature is compared with the assumed gas temperature. If their difference is less than or equal to a specified amount for example one degree K, iteration on that stage is completed. Then boiling temperature at that pressure is checked with Eq. (4.5).

$$T'_{B_c} = \frac{T_{B_c} - [106.46313 \log(1/P_{o,c}) + 0.99316]}{0.12906 \log(1/P_{o,c}) + 4.2952} \qquad (4.5)$$

If the difference of charge bulk temperature and the boiling temperature is less than or equal to a value which is set according to the pressure drop and boiling temperature relation two phase calculations start. If not calculations on next stage is made for single phase.

Second, temperature distribution and charge vapor fraction is calculated for two phase region. Inlet conditions are the output conditions of single phase.

A gas temperature is assumed for stage outlet and heat given by gas is found by Eq. (3.30a). Since the charge is at constant temperature the heat given by flue gas vaporizes the charge. Vapor fraction is given by Eq. (4.6).

$$x_c = \frac{Q_G}{2M_c H_{v_c}} \tag{4.6}$$

Two phase heat transfer coefficient is calculated by subroutine TPHTC. Then, by substituting h_{tp} instead of h_i in Eq. (4.2), T_s is found.

By using Eqs. (3.47), (4.4) a new gas temperature is found and compared with the assumed value. If their difference is less than or equal to a specified amount, for example, one degrees K calculations on that stage is completed. The program preceeds in the same manner until the 24th stage which is ceiling is reached.

Last part is the ceiling region which has the same algorithm as the two phase section the only difference in the equations is 1/3 factor of Q_G and the angle factor in ϕ.

At the end of the calculations in the ceiling region a combustion gas temperature is found for the outlet of the radiation section. This value is compared with the temperature found in convection section. If their difference is less than or equal to a specified amount, for example 10 degree K, the program is terminated, otherwise the assumption made for the combustion gas inlet temperature at the entrance of radiation section is changed according to Eq. (4.7) and the same algorithm is repeated.

$$T_G^{1'} = T_G^1 - (T_G^{N_r+1} - T_G^{N_c+1})\gamma \tag{4.7}$$

where γ equals, 2.5 gives result in least number of iterations for this case.

IV.B DESCRIPTION OF THE PROGRAMS

The furnace program is written in FORTRAN language and is composed of one main program, 11 subroutines, and 18 functions. The flow diagram is given in Figure 4.2. The information is transferred by common blocks between main and subprograms. Digital-Vax computer is used in executing.

In this section the computer program is explained with flowcharts. It is composed of three parts; main program, subroutines and the functions.

1. Main Program

Main program calls subroutine DATA to obtain the input values and subroutine PRINT1 to write the input values. Using equations of Chapter III it calculates specific gravity, mass flowrate, boiling temperature at one atmospheric pressure, critical temperature and inlet density of charge and puts these into common blocks in order to transfer to the subprograms. Then the main program calls subroutines FGFLOR, CONVEC and RADYAS to find the temperature distribution, pressure drop and vapor fraction; and ADIAFT to calculate the percentage error between the heat input to the furnace and heat given by flue gas. It also finds percentage error between heat taken by charge and heat given

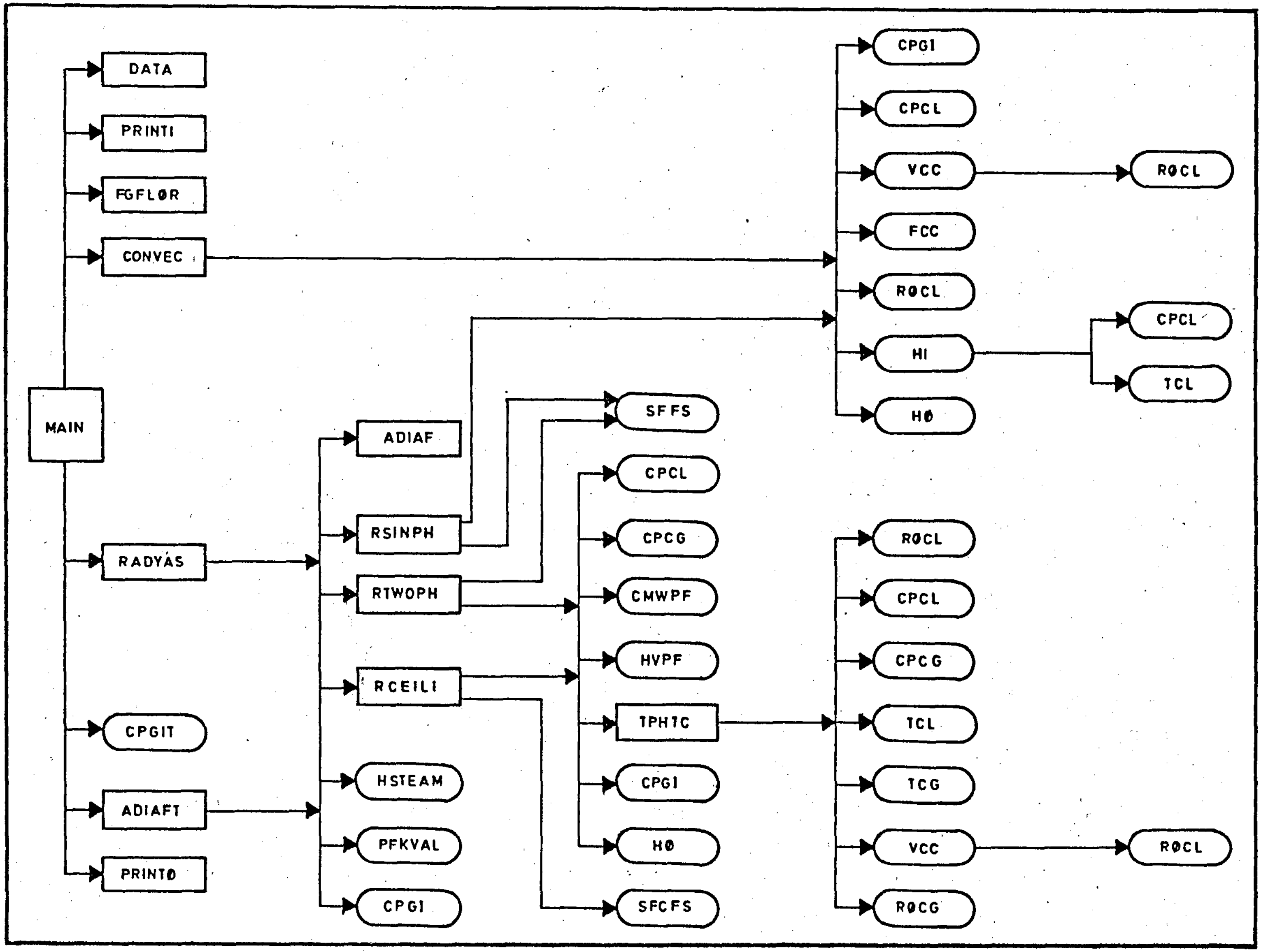

Figure 4.2 Flow Diagram for Programs

by flue gas. At the end it calls PRINTO in order to write the output values. Flowchart is given in Figure 4.3.

2. Subroutines

a) DATA

This subroutine contains input values in nine groups which are data of

Fuel oil: flowrate, %sulfur, API gravity, viscosity and temperature

Fuel gas: flowrate, temperature, pressure and composition

Steam : temperature, pressure

Air : %excess air, %humidity, temperature

Charge : K-factor, temperature, pressure, API, flowrate, two viscosities with corresponding temperatures

Flue gas: Temperature at the stack entrance, total pressure, flame length, average length of radiant beam

Convection Sect.: Inside diameter, outside diameter, length, staggering distance, outside area of tubes; number of tube rows, number of tubes per row, length, height, width of the section

Radiation Sect. : Length, height, width of the section, number of tube rows, outside area, inside and outside diameters and length of tubes.

Reference Condition : Temperature, pressure.

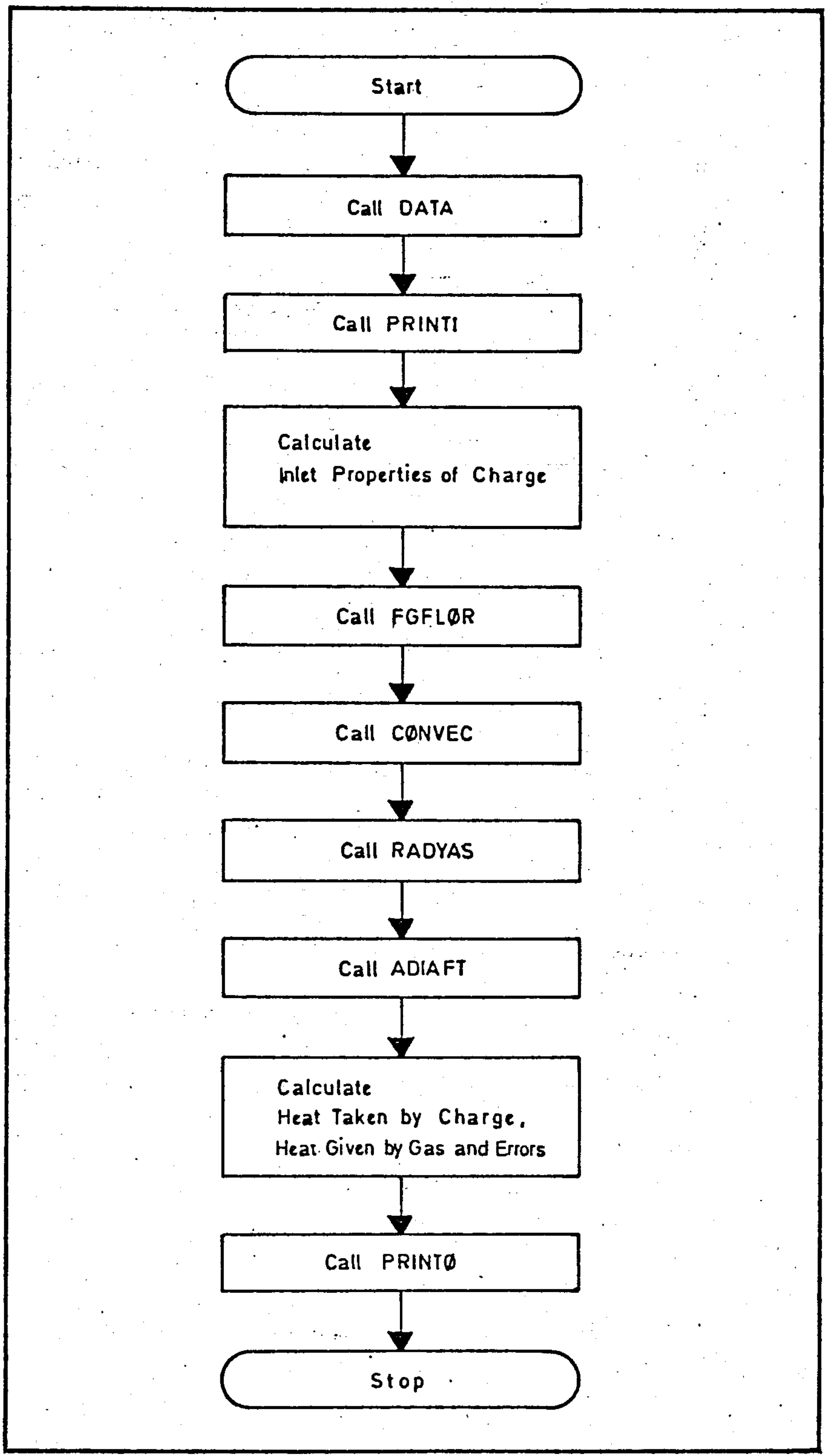

Figure 4.3 Flowchart for Main Program

b. PRINTI

Subroutine PRINTI contains the necessary write statements with formats in order to print the input values in same groups as read.

c. FGFLOR

This subroutine makes the mass balance in the combustion chamber of the furnace. It calculates oxygen needed for complete combustion, adds to this excess oxygen and finds air inlet flow. Then finds the molar flow of combustion products and mole fractions with total molar flow of flue gas based on the equation given in Chapter III.A.1. The flowchart is given in Figure 4.4.

d. CONVEC

According to algorithm given in Section IV.A.1 charge outlet temperatures and pressures for each tube and flue gas temperature at the inlet of each stage is calculated with this subroutine. Before starting the iterations wall area, total tube area, base area, and flue gas flowrate per unit area are found. $Cp_{p,g}$, $Cp_{c,\ell}$, $\mu_{c,\ell}$, h_i, f, $\rho_{c,\ell}$ and h_o are variables used in each stage which are calculated by external functions. The flow chart is given in Figure 4.5.

e. RADYAS

Charge outlet temperatures, pressures, vapor fractions for each tube and flue gas temperatures at the outlet of each stage is

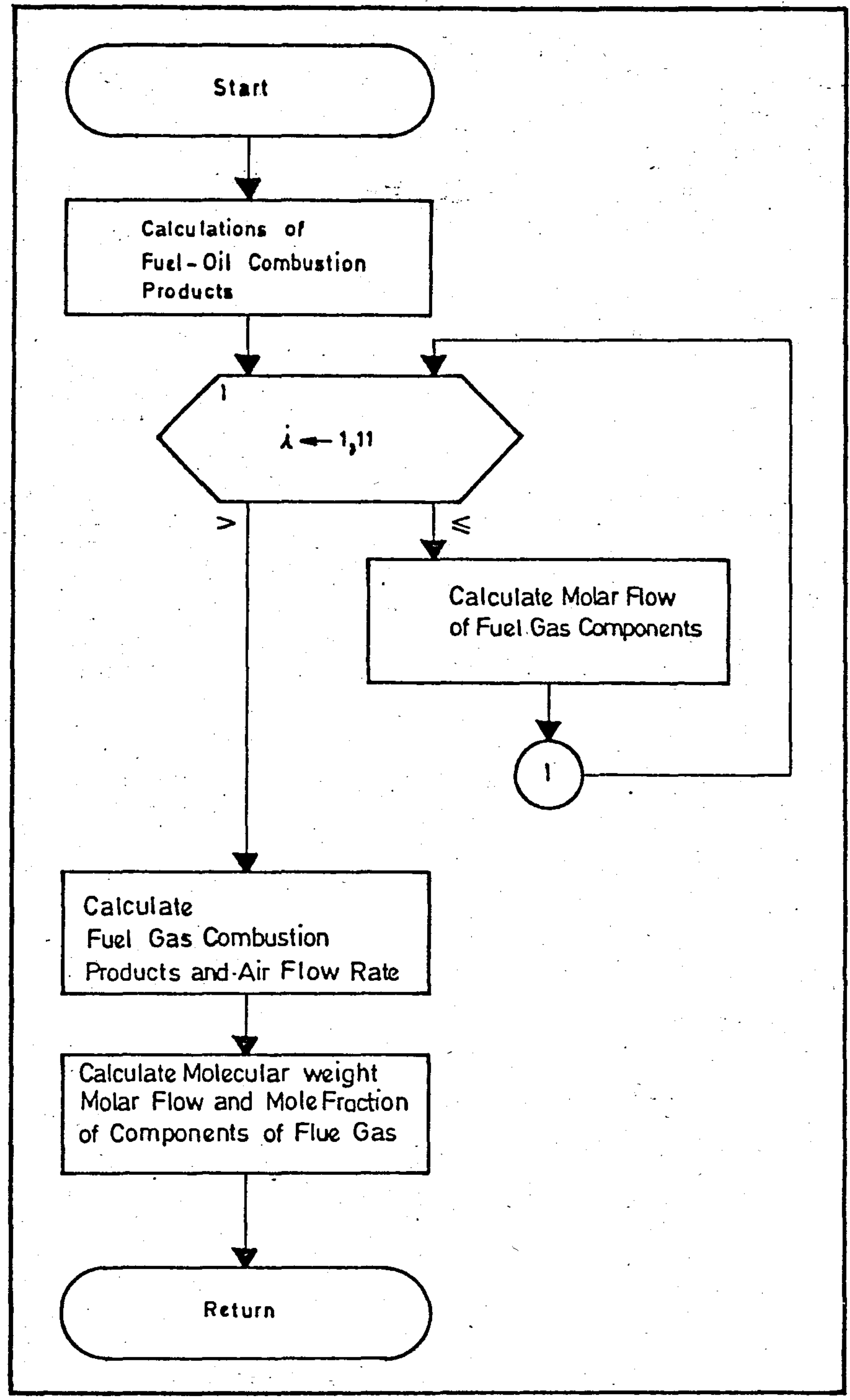

Figure 4.4 Flowchart for Subroutine FGFL0R

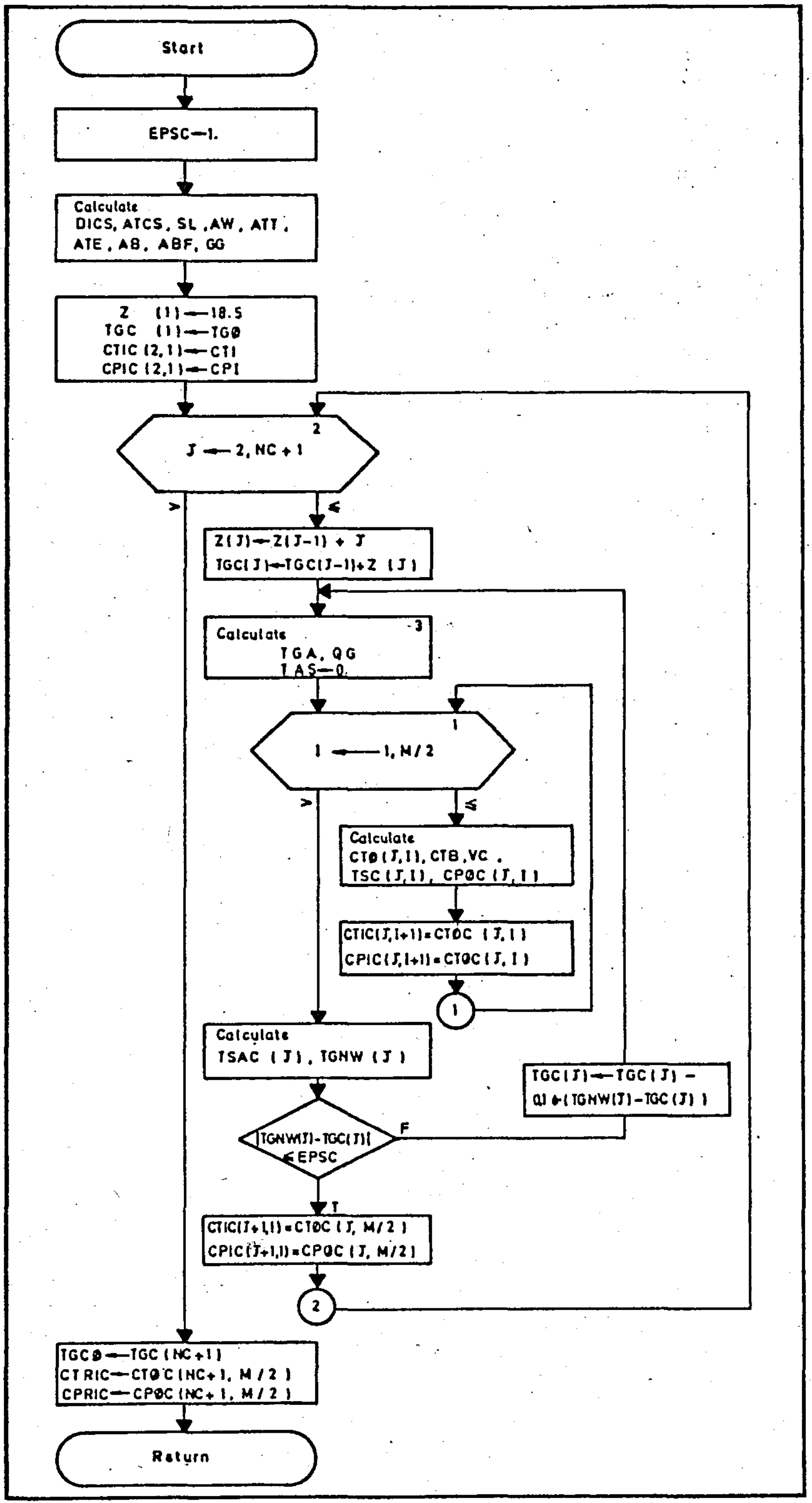

Figure 4.5 Flowchart for Subroutine CONVEC

found with this subroutine by calling RSINPH, RTWOPH and RCEILI. The variables used as constants in the section which are wall, base, total tube and total exchange areas, partial pressure of $CO_2 + H_2O$, flue gas flowrate per unit area are found. Adiabatic flame temperature is calculated by subroutine ADIAF written by Heperkan, H [36]. Flowchart is given in Figure 4.6.

f. RSINPH

According to the algorithm given in Section IV.A.2 charge outlet temperatures, pressures for each tube and flue gas temperature at the outlet of each stage is calculated with this subroutine. If the two phase has not started at the end of 23rd stage, a single phase ceiling calculation is also made. The external functions used in each stage is as the same as in convection section with the addition of ε_f and F_{f-s}. The flow diagram is given in Figure 4.7.

g. RTWOPH

This subroutine is the continuation of RSINPH that gives two phase calculations, instead of pressure drop it finds vapor fraction in each tube. Algorithm is given in Section IV.A.2. The external functions used are the external functions of RSINPH plus $Cp_{c,g}$, $\rho_{c,g}$, H_{v_c}, MW_c, $k_{c,g}$. Two phase heat transfer coefficient is calculated by subroutine TPHTC. The flow diagram is given in Figure 4.8.

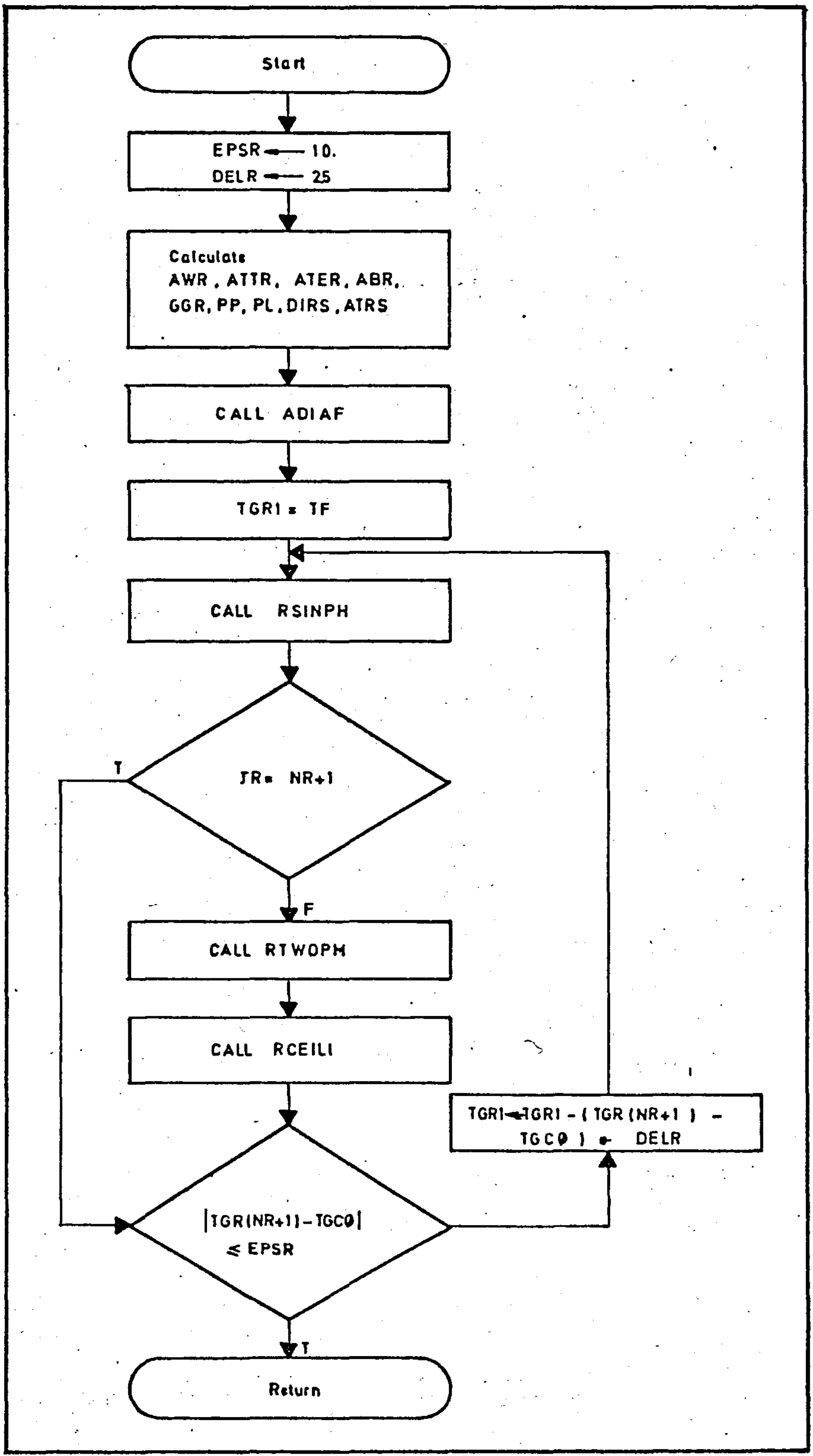

Figure 4.6 Flowchart for Subroutine RADYAS

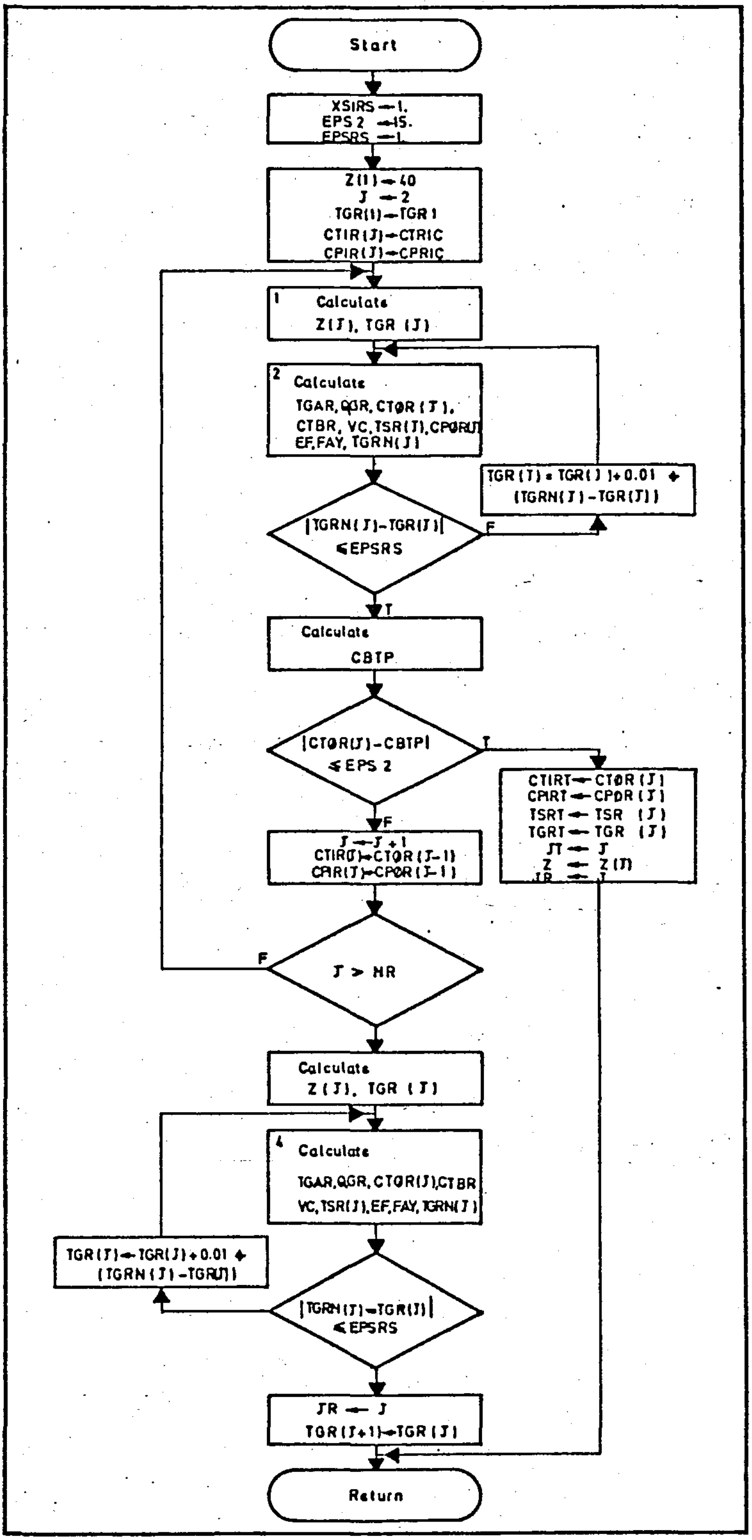

Figure 4.7 Flowchart for Subroutine RSINPH

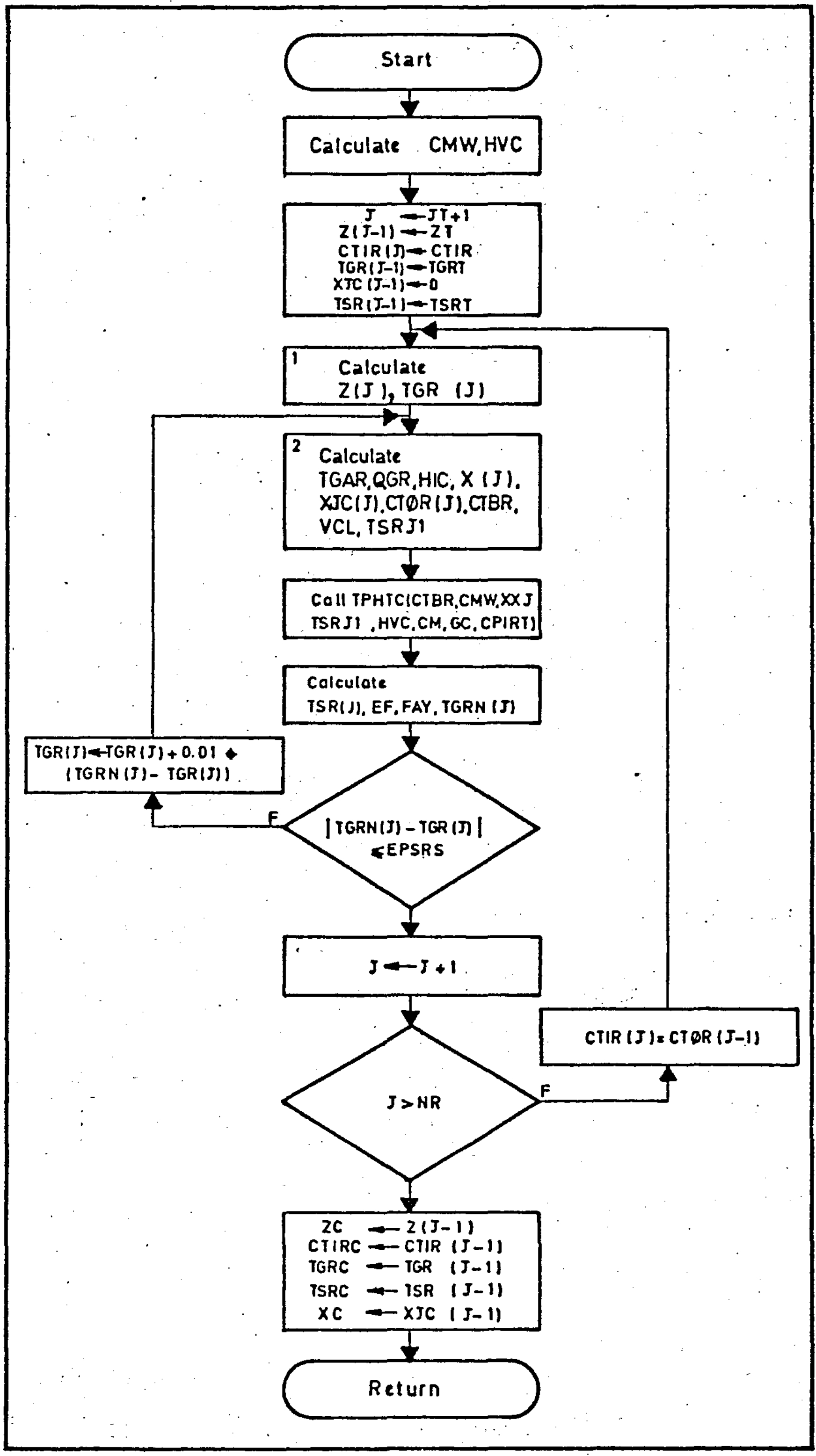

Figure 4.8 Flowchart for Subroutine RTWOPH

h. RCEILI

Charge outlet temperature, vapor fraction and flue gas outlet temperature is found by this subroutine which is the last part of RADYAS. Algorithm and variables used are similar to the RTWOPH. The flowchart is given in Figure 4.9.

i. TPHTC (CTBR, CMW, XJC, TSRJ1, HVC, CM, GC, CPIR)

Two phase heat transfer coefficient is evaluated with this subroutine. Void fraction; densities, viscosities, specific heats, and thermal conductivities for both phases are calculated using the equations of Chapter III. In order to determine the flow pattern superficial velocities are found. According to the flow pattern one of the correlations explained in Section III.B.2 is used to determine the heat transfer coefficient. The flowchart is given in Figure 4.10.

j. ADIAFT

This subroutine is used to make the energy balance in the furnace as explained in Section III.A.2. It calculates the total heat input to the system. The flowchart is given in Figure 4.11.

k. PRINTO

The results of the furnace program is written with this subroutine in five sections which are input variables of charge, results of mass and energy balances, results of convection and radiation section for each stage.

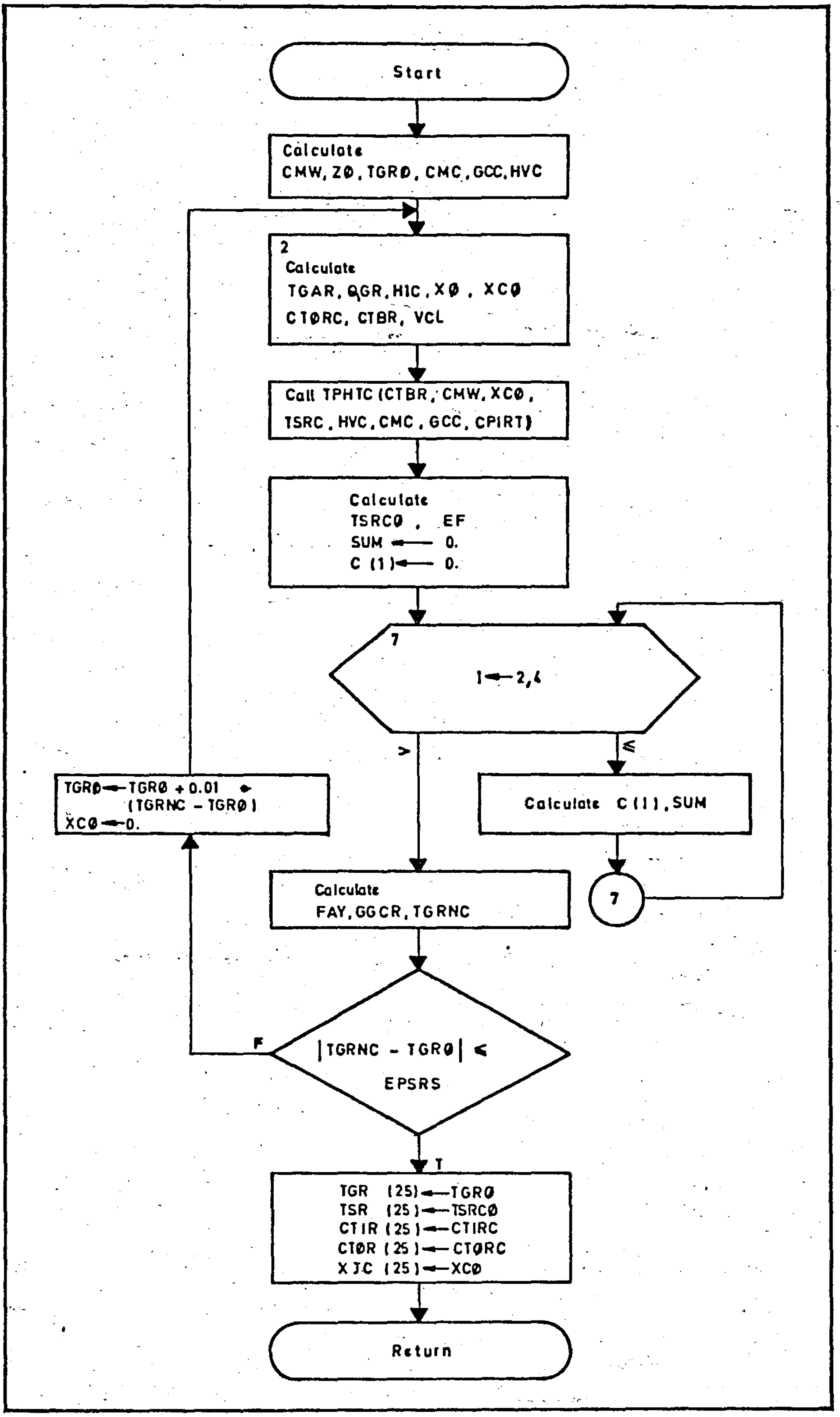

Figure 4.9 Flowchart for Subroutine RCEILI

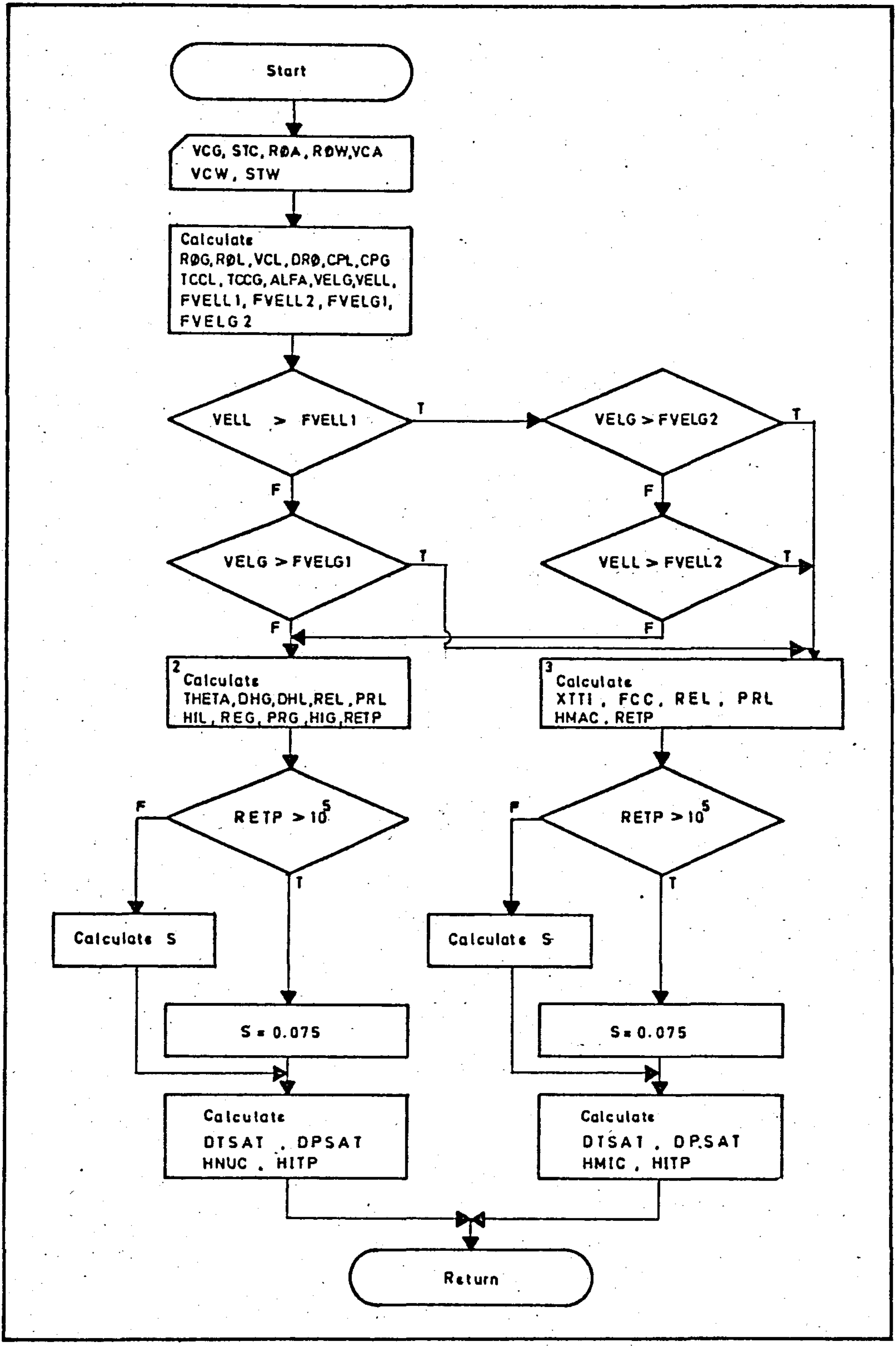

Figure 4.10 Flowchart for Subroutine TPHTC (CTBR, CMW, XJC, TSRJ1, HVC, CM, GC, CPIR)

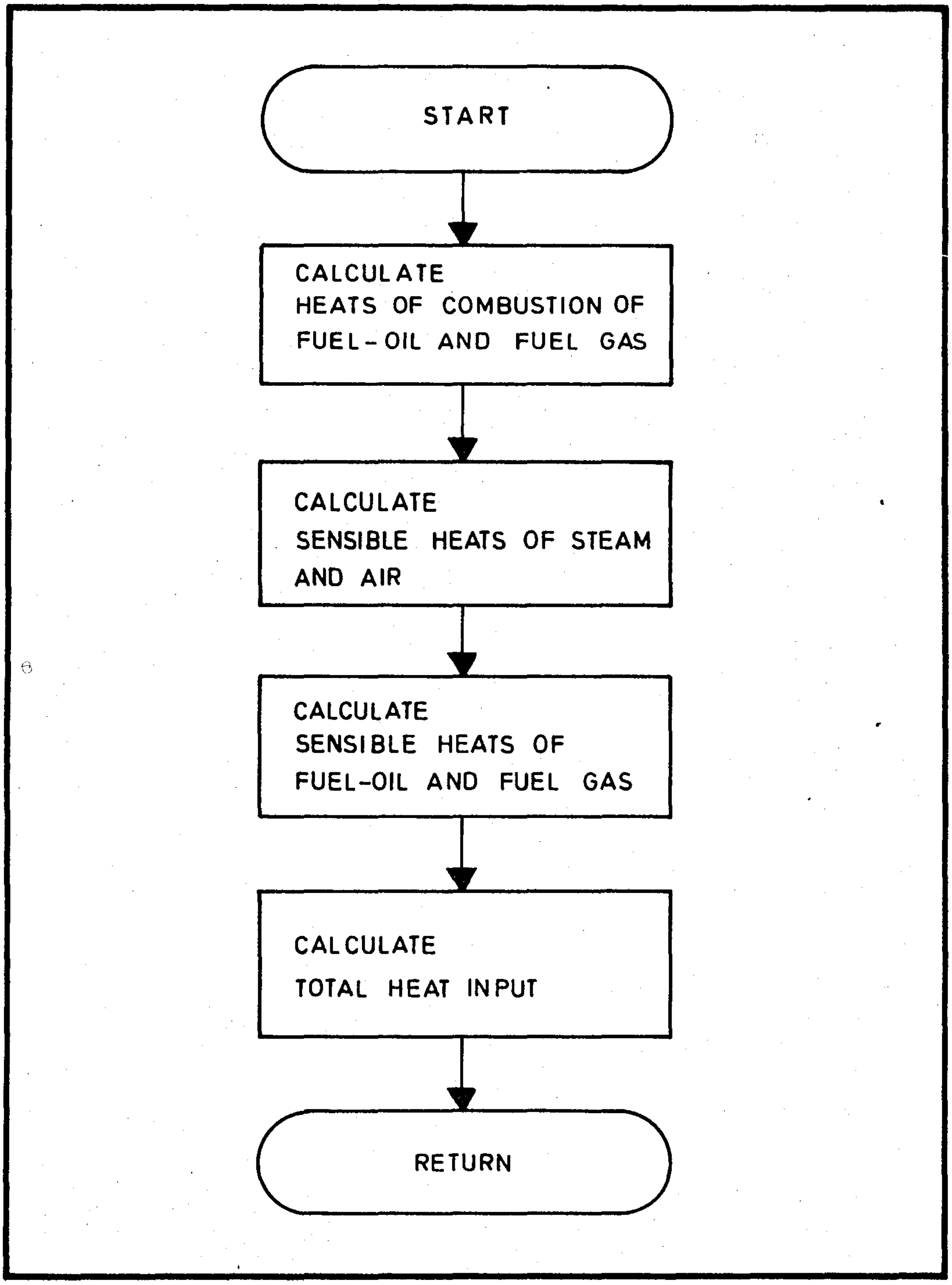

Figure 4.11 Flowchart for Subroutine ADIAFT

3. Functions

a. CPGIT (T)

Calculates the specific heat for flue gas from Eq. (3.31).

b. CPGI (T1,T2)

Calculates the heat capacity of flue gas by integrating the equation used in CPGIT.

c. FFC (VC,DI)

Finds friction factor for tube flow by Newton-Raphson method from Eq. (3.54).

d. HI (VC,T,DI)

Finds single phase heat transfer coefficient for tube flow using Eq. (3.37).

e. HO (TG,TS,GG,DO,AW,AT)

Calculates overall heat transfer coefficient from flue gas to the tubes from Monrad equations.

f. ROCL (T)

Calculates the liquid phase density of petroleum fractions from Eq. (3.39).

g. ROCG (P,T)

Calculates the gas phase density of petroleum fractions after finding the compressibility factor.

h. TCL (T)

Calculates the liquid phase thermal conductivity of petroleum fractions from Eq. (3.38).

i. TCG (T,CMW)

Calculates the gas phase thermal conductivity of petroleum fractions from Eq. (3.100).

j. CPCL (T)

Calculates the liquid phase specific heat of petroleum fractions from Eq. (3.23).

k. CPCG (T)

Calculates the gas phase specific heat of petroleum fractions from Eq. (3.81).

l. VCC (T)

Calculates the liquid phase viscosity of petroleum fractions as explained in Section III.B.1.a by using Newton-Raphson method. Flowchart is given in Figure 4.12.

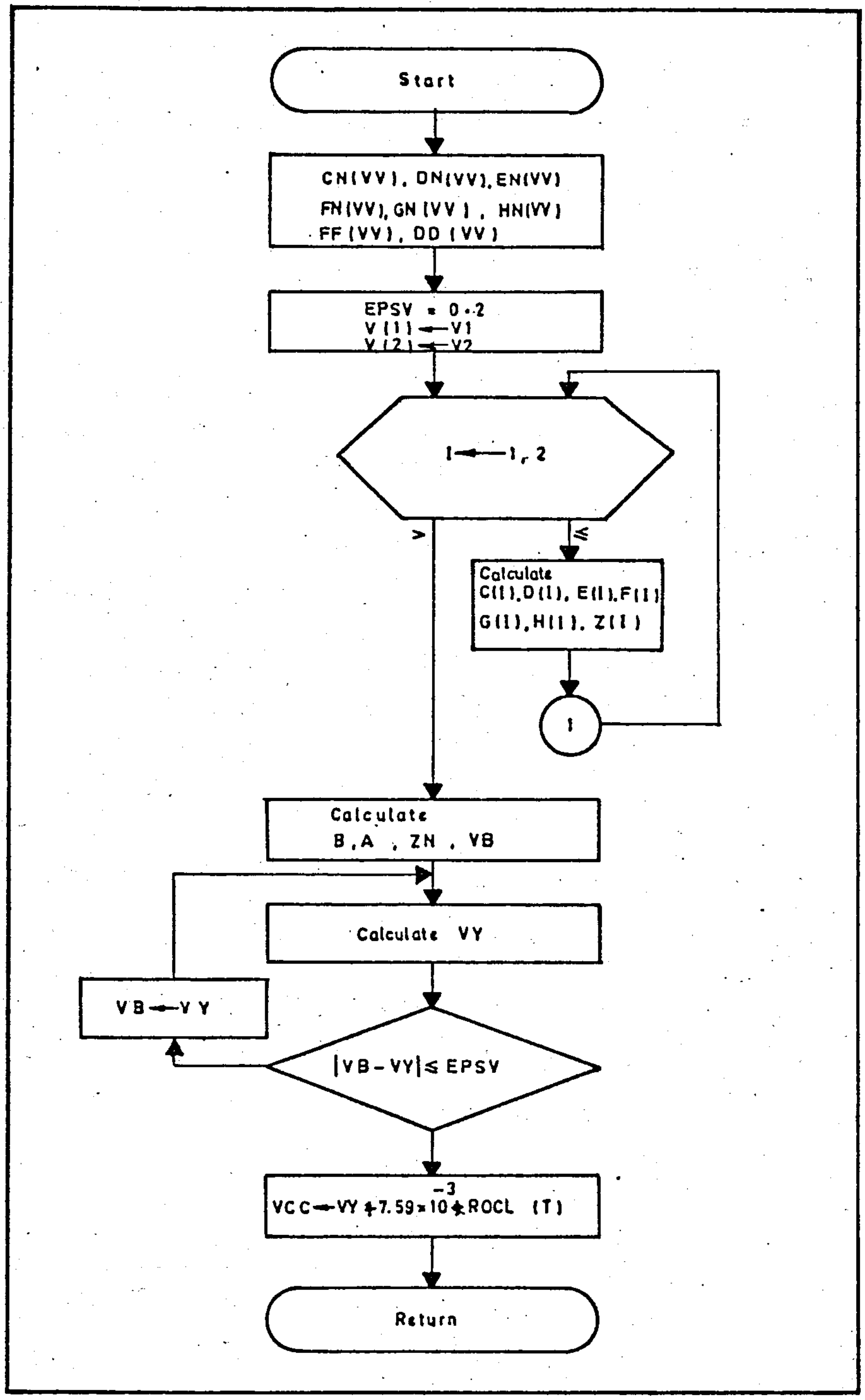

Figure 4.12 Flowchart for Function VCC (T)

m. PFKVAL (V,API)

Calculates the K factor of petroleum fractions from Eq. (3.24).

n. CMWPF (API,K)

Calculates the molecular weight of petroleum fractions from Eq. (3.78).

o. HVPF (CMW,TB)

Calculates the heat of vaporization of petroleum fractions from Eq. (3.77).

p. HSTEAM (T,P)

Calculates enthalpy of steam from Eq. (3.25).

q. SFFS (S)

Finds the angle factor between flame and tubes on the wall of radiation section using Eq. (3.74).

r. SFCFS (C)

Finds the angle factor between flame and tubes on the ceiling of radiation section using Eq. (3.106).

V. RESULTS AND EVALUATION

The results of computerized analysis of the furnace is given in this chapter with evaluation and discussion in two parts. In the first part, the numerical results of the model and effect of change in input parameters on output conditions will be given; in the second part these results will be evaluated.

V.A NUMERICAL RESULTS

The results of computerized analysis of heat transfer in the furnace that has the characteristics given in Tables 2.1, 2.2 and 2.3 for the data set given in Appendix E will be shown graphically; the computer output is in Appendix F.

The necessary input variables of charge are calculated to be:

Mass flow in each coil = 1.358x10 kg/hr

Specific gravity = 0.932

Critical temperature = 863.5°K

Boiling temperature at 1 atm. = 715.2°K

Mass and energy balances on the combustion side are used to find these variables:

Mass flow of steam = 586.5 kg/hr
Molar flow of air = 1592 kmole/hr
Molar flow of flue gas = 1720 kmole/hr
Molecular weight of flue gas = 28.6 kg/kmole
Mole fraction of components of flue gas = CO_2 = 0.103
H_2O = 0.126
SO_2 = 0.002
O_2 = 0.036
N_2 = 0.733
Adiabatic flame temperature = 1995°K

Flue gas mass flow rate in convection section is 5784 kg/m^2-hr and in radiation is 654.4 kg/m^2-hr.

The charge outlet temperature from each stage is shown in Figure 5.1 that has temperature (°K) at vertical axis and number of stage at horizontal axis. The numbers from 1 to 6 corresponds to convection section stages and from 7 to 30 corresponds to radiation section stages.

Figure 5.2 is the graph of the charge outlet vapor fraction from each stage with mass fraction at the vertical axis and number of stage, as described above, at the horizontal axis.

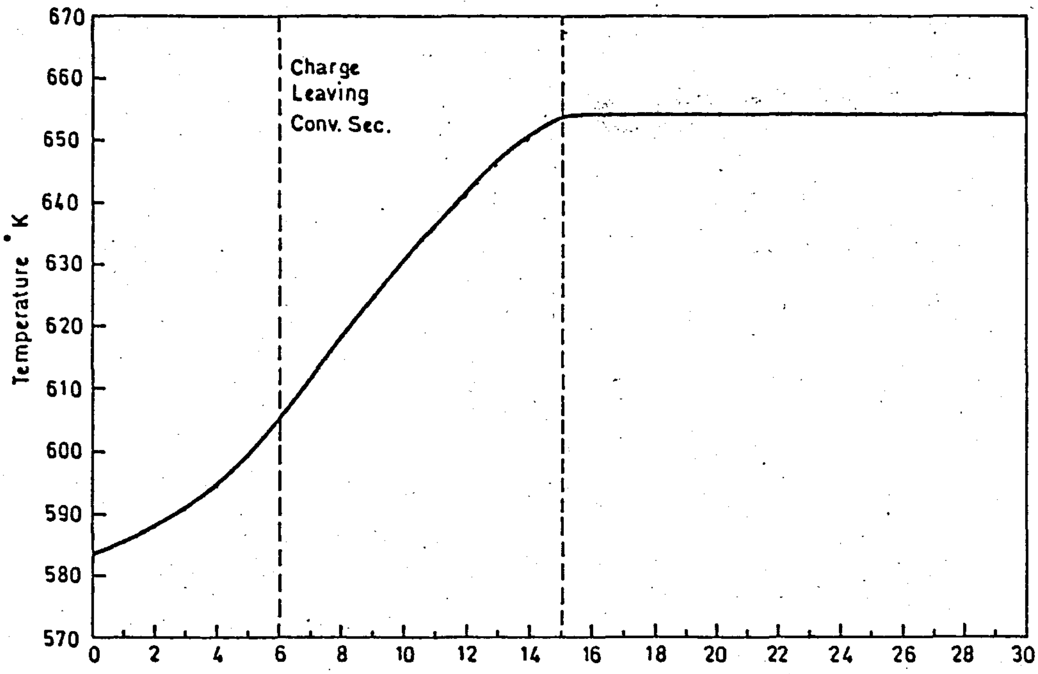

Figure 5.1 Charge Outlet Temperature from Each Stage

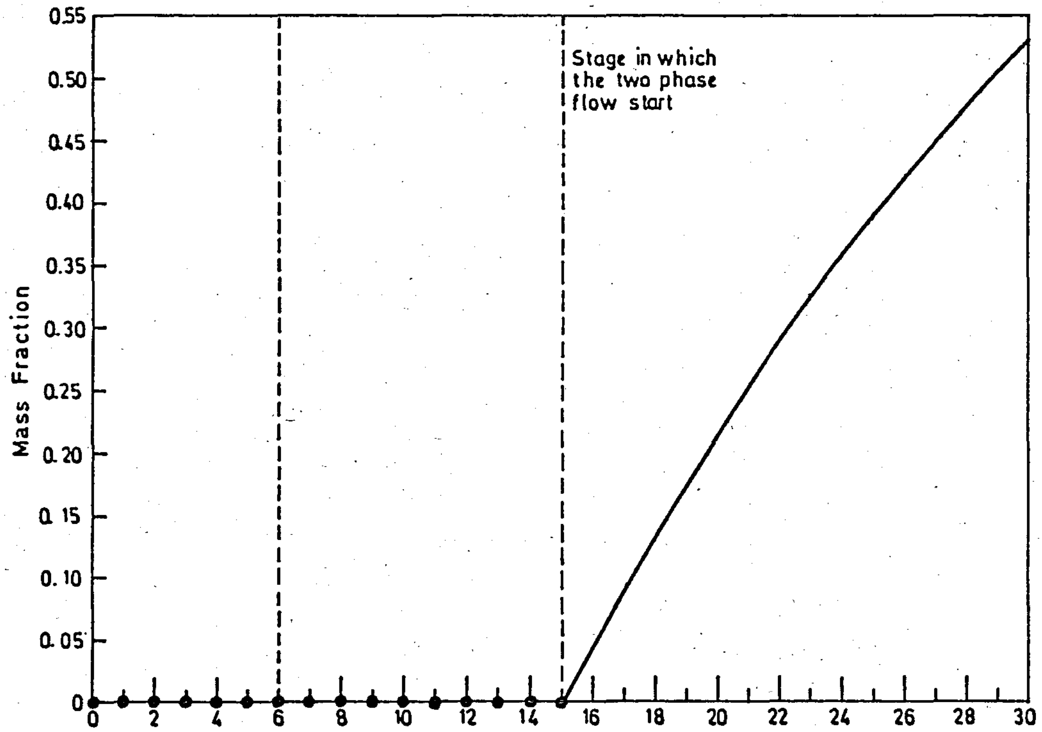

Figure 5.2 Charge Outlet Vapor Fraction from Each Stage

Temperature distribution of the combustion (flue) gas in the furnace is plotted in Figure 5.3 which has temperature at vertical axis and number of stage at horizontal axis the number from 1 to 24 at horizontal axis corresponds to radiation section stages and from 25 to 30 to convection stages from 6 to 1.

In the convection, the validity of the model is checked with the temperature of the flue gas entering the section by comparing the measured value which is 989°K and calculated value which is 988.5°K. The difference of 0.5°K gives 0.05% error. The assumption of no heat loss to the surroundings resulted charge temperature of 604.7°K. Since there is no measured value corresponding to charge outlet temperature from the section, the error in calculation cannot be found. This also true for charge outlet pressure which is calculated to be 1.71 atm that corresponds to pressure drop of 2.16 atm.

The change in charge temperature flowing down the furnace at the sides from outside during transportation from convection section to radiation section is neglected. The measured charge outlet temperature is 638°K but the calculated value is 654°K. This gives error of -2.5%. The vaporization of charge starts at 10th stage of radiation section and 53.7% of charge vaporizes at constant temperature, this has deviation from design value of -0.75%. The pressure drop is not calculated in two phase flow because it is needed to predict the starting stage of vaporization. Combustion gas temperature at the outlet of radiation section is 988.98°K which deviates from the measured value of 988°K by 0.002%.

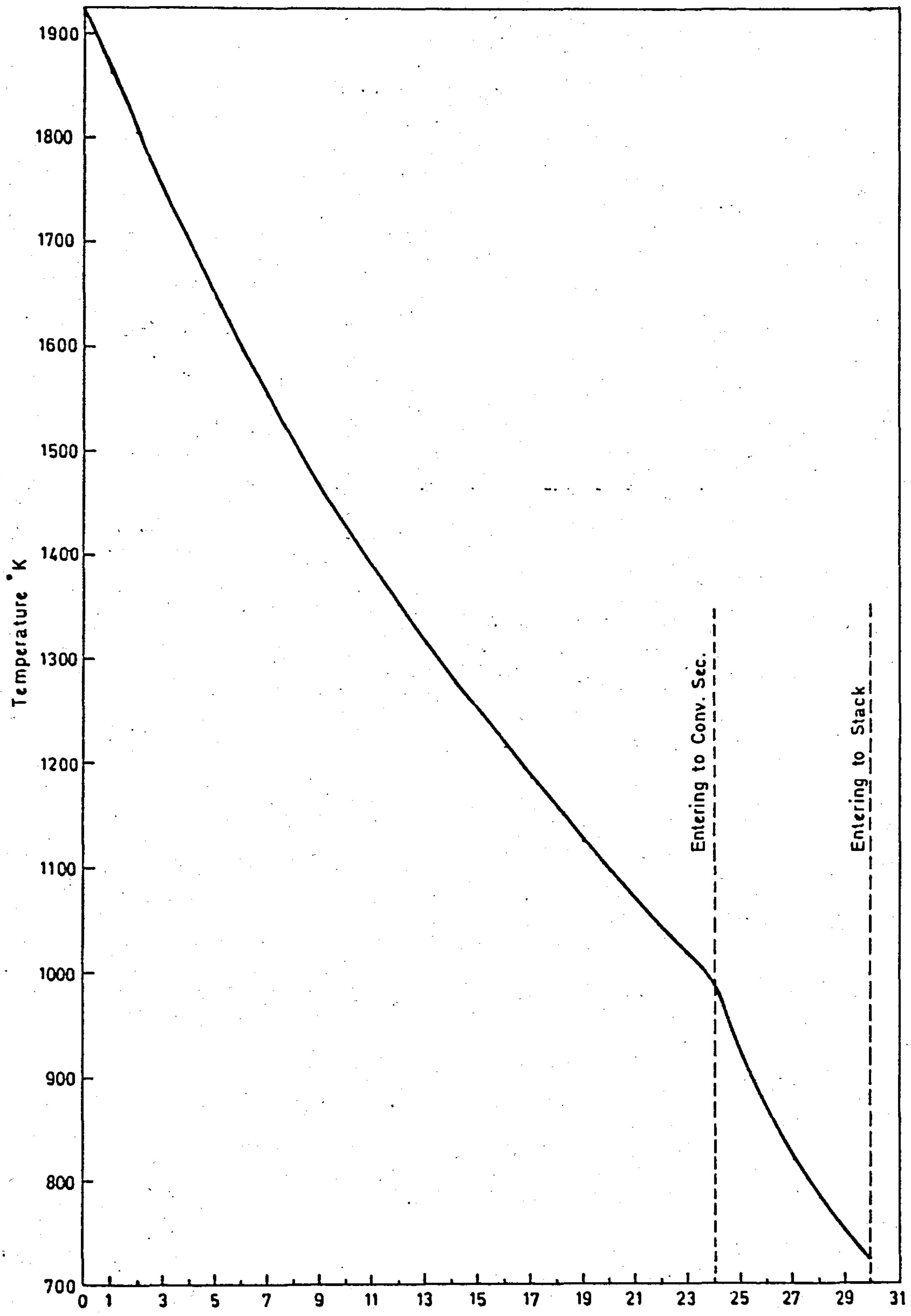

Figure 5.3 Flue Gas Temperature Distribution

After seeing the validity of the furnace model with the results given above the effect of change in input parameters and heat transfer coefficients on output conditions such as temperatures and vaporization is determined and they are given in Tables 5.1 and 5.2.

TABLE 5.1 - Changes in Heat Transfer Coefficients

Changes in h	Changes in charge				Changes in flue gas		
	outlet T (°K)	Press.(atm) when vap. starts	st. # at which vap. starts	Vapor fraction	T_f (°K)	inlet T (°K)	inlet T (°K) to conv. sec.
no charge	654.1	0.35	10	0.54	1995	1923	988
1.3 h_i	655.0	0.35	10	0.54	1995	1932	992
0.7 h_i	652.7	0.35	10	0.53	1995	1906	982
1.05 h_o	662.4	0.34	10	0.59	1995	2020	1011
0.95 h_o	650.3	0.20	11	0.45	1995	1832	967
1.3 h_{tp}	654.2	0.35	10	0.54	1995	1924	988
0.7 h_{tp}	654.0	0.34	10	0.53	1995	1920	988

As shown in Table 5.1 charge outlet temperature and vapor fraction is not very sensitive to heat transfer coefficients on the inside. 30 percent increase or decrease of single and two phase coefficients changed output conditions less than 0.2 percent. When the heat transfer coefficient on the outside is changed by 5 percent both flue gas temperature and charge outlet conditions are affected which are summarized in Table 5.3.

TABLE 5.2 - Changes in Input Parameters

Changes in input parameters	Changes in charge				Changes in flue gas		
	outlet T (°K)	Press (atm) when vap. starts	st # at which vap. starts	Vapor fraction	T_f (°K)	inlet T (°K)	inlet T (°K) to conv. sec.
no change	654.1	0.35	10	0.54	1995.2	1923	988
charge: 1.1K	685	-	-	-	1995.2	1912	990
0.9K	613	1.36	2	>1	1995.2	1894	988
$1.1T_i$	679	0.47	8	0.48	1995.2	1594	874
$0.9T_i$	640	0.21	12	0.57	1995.2	2249	1098
$1.1P_i$	661	0.42	12	0.44	1995.2	1915	988
$0.9P_i$	646	0.27	8	0.65	1995.2	1932	988
1.25API	637	0.99	6	0.80	1995.2	1934	988
0.75API	690	-	-	-	1995.2	1904	989
1.25V	673	-	-	-	1995.2	1937	994
0.75V	704	1.06	19	0.21	1995.2	1854	980
Flue gas: $1.03T_o$	665	0.48	9	0.69	1995.2	2135	1074
$0.97T_o$	643	0.21	11	0.42	1995.2	1724	905
$1.25P_{tt}$	654	0.35	10	0.54	1995.2	1923	988
$0.75P_{tt}$	654	0.35	10	0.54	1995.2	1923	988
$1.5\ L_f$	664	0.35	10	0.64	1995.2	2079	988
$0.5\ L_f$	649	0.20	11	0.42	1995.2	1800	986
Air : 1.43 Ex.	647	0.20	11	0.42	1899.4	1733	971
0.57 Ex.	667	0.34	10	0.63	2097.3	2167	1010
$1.03\ T_i$	655	0.35	10	0.54	1996.9	1994	992
$0.97\ T_i$	653	0.35	10	0.53	1993.5	1901	986
Fuel oil: 1.15 V	649	0.20	11	0.45	1995.0	1724	958
0.85 V	666	0.34	10	0.59	1995.3	2196	1027
1.12 API	654	0.35	10	0.54	1991.2	1929	990
0.88 API	654	0.35	10	0.54	2006.9	1923	988
$1.14\ \nu$	654	0.35	10	0.54	1995.2	1923	988
$0.86\ \nu$	654	0.35	10	0.54	1995.2	1923	988
Fuel gas: 1.5 V	647	0.21	11	0.44	1995.7	1667	948
0.5 V	667	0.49	9	0.69	1994.6	2310	1042
$1.03\ T_i$	655	0.35	10	0.54	1995.2	1943	991
$0.97\ T_i$	653	0.35	10	0.53	1995.2	1902	986
comp 1	646	0.21	11	0.44	1996.4	1653	947
comp 2	655	0.35	10	0.55	1995.4	1955	994

Changes in compositions of fuel gas in Table 5.2 are:

Comp 1 = 0.007 H_2S, 0.001 H_2, 0.144 N_2, 0.111 O_2, 0.004 CO_2, 0.009 CO, 0.014 C_1, 0.443 C_2, 0.220 C_3, 0.047 I-C_4

Comp 2 = 0.003 H_2S, 0.001 H_2, 0.39 N_2, 0.127 O_2, 0.004 CO_2, 0.009 CO, 0.011 C_1, 0.313 C_2, 0.115 C_3, 0.010 I-C_4, 0.001 N-C_4

TABLE 5.3 - Percent Changes in h_0 and Outputs

h_0	Charge outlet		Flue gas	
	T (°K)	x	inlet T (°K)	inlet T to conv. sec.
5	-1.22	-9.26	-5.04	-2.22
-5	0.61	16.67	4.73	2.22

Changes in flue gas total pressure, fuel oil inlet viscosity and fuel gas inlet temperature does not effect output conditions much as seen from Table 5.2. The effect of percentage change in input variables other than those are given in Table 5.4.

Holding change outlet temperature in a narrow range is important because it affects the operation of vacuum column for example charge outlet temperature of 668°K changes the operation of the vacuum column [32] this corresponds to error of -1.7 percent. Therefore fuel flowrates, percent excess air, flue gas temperature, flame length and inlet conditions of charge must be controlled in order not to change charge outlet conditions severely.

V.B EVALUATION OF RESULTS

The assumptions made and the empirical correlations used are affected the results of the computerized analysis of the furnace.

One dimensional heat transfer is assumed in the model. It is in vertical direction for the flue gas. This assumption for convection section is better than for radiation because the mass flowrate

TABLE 5.4 - Percent Changes of Inputs and Outputs

Input Parameters		Charge outputs		Flue gas		
		T (°K)	x	T_f (°K)	T_i	inlet T(°K) to conv. sec.
charge K	: 10	-4.7	100	0.0	0.6	-0.2
	-10	6.3	>100	0.0	1.5	0.0
T_i	: 10	-3.8	11.1	0.0	17.1	11.5
	-10	2.1	-5.6	0.0	-17.0	-11.1
P_i	: 10	-1.1	18.5	0.0	0.4	0.0
	-10	1.2	-20.4	0.0	-0.5	0.0
API	: 25	2.5	-48.1	0.0	-0.5	0.0
	-25	-5.5	100	0.0	1.0	-0.1
V	: 25	-2.9	100	0.0	-0.7	-0.6
	-25	7.6	61.1	0.0	3.6	0.8
Flue gas T_o	: 3	-1.7	-27.8	0.0	-11.0	-8.7
	-3	1.7	22.2	0.0	10.3	8.4
L_f	: 50	-1.5	-18.5	0.0	-8.1	0.0
	-50	0.8	22.2	0.0	6.4	-0.2
Air excess	: 43	1.1	22.2	4.8	9.9	1.7
	-43	-2.0	-18.4	-5.1	-12.7	-2.2
T_i	: 3	-0.2	0.0	-0.09	-1.1	-0.6
	-3	0.2	1.9	0.09	1.1	0.2
Fuel oil V	: 15	0.8	16.7	0.01	10.3	3.0
	-15	-2.0	-9.3	-0.01	-14.2	-3.9
API	: 12	0.0	0.0	0.2	-0.3	-0.2
	-12	0.0	0.0	-0.6	0.0	0.0
Fuel gas V	: 50	1.1	18.5	-0.03	13.3	4.0
	-50	-2.0	-27.8	0.03	-20.1	-5.4
comp 1		1.1	18.5	-0.06	14.0	4.1
comp 2		-0.2	-1.9	-0.01	-1.7	-0.6

is approximately nine times greater in convection section which means more turbulance. Since 14 burners are placed evenly on the centerline temperature along the length of the furnace in the radiation section can assumed to be constant but there is a temperature gradient towards the side walls where the tubes are placed. This gradient is neglected therefore combustion gas temperature at the inlet of the section is resulted to be higher. The heat transfer is assumed to be only in axial, flow direction. Because the Reynolds number has magnitude of 10^6 this can be valid.

The tube surface temperature is assumed to be constant but in reality it changes both in the axial and angular direction. This assumption is made stronger with the assumption of negligible resistance of tube wall to conduction. It can be valid because of high thermal conductivity of metals.

It is assumed that there is no heat loss to the surroundings in the furnace and during transportation from convection section to radiation section. This resulted higher charge outlet temperature and vapor fraction.

The assumption of complete combustion, therefore higher flame and gas temperature also resulted in higher charge outlet conditions.

The vaporization is assumed to take place at constant temperature and pressure. This means the pressure drop due to fraction is compensated with the vapor pressure of the fluid, but in reality since these two pressure changes are not equal the vaporization temperature is not constant.

The flame is assumed to be planar due to the setting of the burners with constant temperature. The combustion gas is assumed to be non-participating that is radiant transfer is between flame and tube banks. These two assumption also resulted in higher charge outlet conditions.

The second factor besides the assumptions made that affect the charge outlet conditions is the empirical correlations that are used. These are mostly for properties of charge, all of which found in literature some in equational form others in graphical form. For the ones in graphical forms equations are curve fitted by the author. Error in curve fitting is added up to the experimental errors made during obtaining the graphs. Since no experimental work was possible those equations are used without knowing the error that they carry. This is also true for the heat transfer coefficients that are used.

VI. CONCLUSION

In this study, a mathematical model for the multiple fuel fired, Born type refinery furnace is derived and solved by numerical methods using computer programs developed.

The validity of the model is checked with one set of data because there is no any other complete set for the furnace analyzed. When the results are compared with the corresponding measured values the errors are less than 2.5 percent.

First part of the model which is for convection section is more realistic than the second part which is for the radiation section because the fluid flow and heat transfer have mechanisms in radiation section are more complex to model.

Although two phase flow pattern shows continuous wetting on tube walls which means use of Chen correlation in predicting h_{tp} for the studied case, the correlation used to predict h_{tp} when top wall of the tube is dry is also included in the model to give generality.

The model has some restrictions which are:

1. It is for steady-state therefore transition solutions cannot be obtained with it.
2. Furnace must have symmetrical two coil arrangement.
3. In the analyzed furnace boiling takes place in radiation section. If it is to be used for furnaces which have boiling in convection section, that section must be modified by adding two phase flow.

The computer program is written in the form of series of subprograms in order to give flexibility to the user. And it can be used for furnaces that have different number of tubes with only changing the data.

As observed from sensitivity analysis the charge inlet conditions, fuel flowrate and percentage of excess air need careful controlling.

The development model can be adapted to the control algorithm and it can also be used in calculations of optimal operation conditions in the furnace.

Instead of using empirical correlations and graphs found in literature for properties of flowing streams and heat transfer coefficients, correlations for this furnace can be determined experimentally if one can make a number of test-runs and collect data on characteristics of flowing streams, temperature distributions and pressure drop in tubes. Then as a result a improved model can be developed.

APPENDICES

APPENDIX A

DERIVATION OF CURVE FITTED EQUATIONS

This chapter explains how the equations for enthalpy of water; K factor, molecular weight, gas phase thermal conductivity, critical pressure and boiling temperature below atmospheric pressure for petroleum fractions; and convective heat transfer correction and nucleate boiling suppression factors in Chen correlation are determined.

The equations for Chen correlation are obtained by the computer program which uses Least Squares Method.

The others are obtained by the computer program which uses statistical package for multiple regression in two steps because they have the form of $y = f(x,z)$. First z is held constant and relation between x and y is found, then the relation between z and constants in first part is calculated. The accuracy of the equation is checked with two parameters of the method [37] which are R^2 coefficient of determination and F (F test). As R^2 tends to unity and F goes to higher values accuracy increases.

The final form of the fitted equation is determined after the trial of different forms which are polynomials of x and x^{-1} with degrees up to five and logarithmic and exponential forms.

A.1 ENTHALPY OF STEAM

Fitted equation for enthalpy (Btu/lb) of steam as function of temperature (°F) and pressure (psia) is found using 171 points which are read from the steam tables [38].

First pressure is held constant and relation between enthalpy and temperature is found.

$$H = a + bT \qquad (A.1.1)$$

SEQNUM	TEMPERATURE (°F)
1	250
2	300
3	340
4	350
5	360
6	380
7	400
8	420
9	440
10	450
11	460
12	480
13	500
14	520
15	540
16	550
17	560
18	580
19	600

For P = 14.696 psia

a = 1050.84991   b = 0.47239 R^2 = 0.99932

F = 25160.024

```
            OBSERVED           PREDICTED
SEQNUM        H01                 H01              RESIDUAL

     1      1169.200           1168.947           .2530457
     2      1192.000           1192.566          -.5663600
     3      1214.000           1211.462           2.538113
     4      1215.400           1216.186          -.7857749
     5      1220.000           1220.910          -.9096506
     6      1231.000           1230.357           .6425859
     7      1238.900           1239.805          -.9051837
     8      1249.000           1249.253          -.2529411
     9      1258.000           1258.701          -.7007046
    10      1262.100           1263.425          -1.324596
    11      1268.000           1268.148          -.1484682
    12      1280.000           1277.596           2.403768
    13      1285.400           1287.044          -1.644001
    14      1298.000           1296.492           1.508241
    15      1305.000           1305.940          -.9395222
    16      1311.000           1310.663           .3365960
    17      1316.000           1315.387           .6127143
    18      1326.000           1324.835           1.164951
    19      1333.000           1334.283          -1.282813
```

For P = 20 psia

a = 1048.24230   b = 0.47559 R^2 = 0.99967

F = 51328.89311

```
            OBSERVED           PREDICTED
SEQNUM        H02                 H02              RESIDUAL

     1      1168.000           1167.140           .8604048
     2      1191.100           1190.919           .1809365
     3      1210.000           1209.943           .5737838-01
     4      1214.800           1214.699           .1014743
     5      1219.000           1219.454          -.4544053
     6      1230.000           1228.966           1.033811
     7      1238.400           1238.478          -.7797870-01
     8      1248.000           1247.990           .1024374-01
     9      1256.000           1257.502          -1.501540
    10      1261.600           1262.257          -.6574409
    11      1266.000           1267.013          -1.013324
    12      1276.000           1276.525          -.5251072
    13      1285.000           1286.037          -1.036891
    14      1296.000           1295.549           .4513255
    15      1305.000           1305.060          -.6045821-01
    16      1311.000           1309.816           1.183650
    17      1315.000           1314.572           .4277581
    18      1326.000           1324.084           1.915974
    19      1332.700           1333.596          -.8958122
```

For P = 50 psia

a = 1038.49799 b = 0.48996 R^2 = 0.99944

F = 28667.69685

SEQNUM	OBSERVED H03	PREDICTED H03	RESIDUAL
2	1184.600	1185.485	-.8847358
3	1205.000	1205.083	-.8295815-01
4	1210.300	1209.983	.3174718
5	1215.000	1214.882	.1179261
6	1224.000	1224.681	-.6811896
7	1235.200	1234.480	.7196916
8	1245.000	1244.279	.7205789
9	1254.000	1254.079	-.7853685-01
10	1258.600	1258.978	-.3781039
11	1265.000	1263.878	1.122347
12	1273.000	1273.677	-.6767683
13	1282.600	1283.476	-.8758932
14	1294.000	1293.275	.7250002
15	1302.000	1303.074	-1.074116
16	1311.000	1307.974	3.026327
17	1313.000	1312.873	.1267687
18	1322.000	1322.672	-.6723470
19	1331.000	1332.471	-1.471463

For P = 100 psia

a = 1021.70281 b = 0.51418 R^2 = 0.99822

F = 8404.08424

SEQNUM	OBSERVED H04	PREDICTED H04	RESIDUAL
3	1194.900	1196.524	-1.624221
4	1200.000	1201.666	-1.666021
5	1207.000	1206.808	.1921729
6	1218.300	1217.091	1.208549
7	1228.400	1227.375	1.024943
8	1238.600	1237.659	.9413277
9	1247.000	1247.942	-.9422752
10	1253.700	1253.084	.6159158
11	1259.000	1258.226	.7741128
12	1268.000	1268.509	-.5094992
13	1278.600	1278.793	-.1931204
14	1290.000	1289.077	.9232768
15	1298.000	1299.360	-1.360335
16	1310.000	1304.502	5.497859
17	1308.000	1309.644	-1.643947
18	1319.000	1319.928	-.9275592
19	1327.000	1330.211	-2.311177

For P = 150 psia

a = 1009.90063 b = 0.52587 R^2 = 11579.24469

F = 11579.24469

SEQNUM	OBSERVED H05	PREDICTED H05	RESIDUAL
5	1198.000	1199.213	-1.213417
6	1208.400	1209.731	-1.330801
7	1220.000	1220.248	-.2481720
8	1231.400	1230.766	.6344446
9	1242.000	1241.283	.7170734
10	1248.000	1246.542	1.458385
11	1250.000	1251.800	-1.800304
12	1265.000	1262.318	2.682319
13	1274.100	1272.835	1.264932
14	1284.000	1283.352	.6475642
15	1295.000	1293.870	1.130187
16	1293.000	1299.128	-1.128502
17	1303.000	1304.387	-1.387190
18	1314.000	1314.905	-.9045677
19	1324.900	1325.422	-.5219511

For P = 200 psia

a = 996.95477 b = 0.54237 R^2 = 0.99842

F = 6955.26251

SEQNUM	OBSERVED H06	PREDICTED H06	RESIDUAL
7	1210.800	1213.902	-3.101732
8	1223.700	1224.749	-1.049070
9	1236.300	1235.596	.7035733
10	1242.000	1241.020	.9799117
11	1247.900	1246.444	1.456232
12	1258.700	1257.291	1.408887
13	1269.400	1268.138	1.261537
14	1280.000	1278.986	1.014195
15	1290.000	1289.833	.1668479
16	1295.600	1295.257	.3431650
17	1300.000	1300.680	-.6804997
18	1310.000	1311.528	-1.527847
19	1321.400	1322.375	-.9752008

For P = 250 psia

a = 980.53536　　b = 0.56367　　R^2 = 0.99786

F = 4670.01312

```
             OBSERVED           PREDICTED
SEQNUM         H07                 H07           RESIDUAL
   8        1214.600            1217.276        -2.675986
   9        1228.300            1228.549        -.2493522
  10        1233.000            1234.186        -1.186021
  11        1241.000            1239.823         1.177297
  12        1253.200            1251.096         2.103931
  13        1264.700            1262.369         2.330568
  14        1274.500            1273.643         .8572085
  15        1285.000            1284.916         .8384568-01
  16        1291.600            1290.553         1.047155
  17        1295.000            1296.190        -1.189517
  18        1306.000            1307.463        -1.462880
  19        1317.900            1318.736        -.8362490
```

For P = 300 psia

a = 957.01353　　b = 0.59837　　R^2 = 0.99684

F = 3154.87961

```
             OBSERVED           PREDICTED
SEQNUM         H08                 H08           RESIDUAL
   8        1205.200            1208.328        -3.127598
   9        1219.500            1220.295        -.7949316
  10        1225.000            1226.279        -1.278600
  11        1233.400            1232.262         1.137726
  12        1246.600            1244.230         2.370387
  13        1259.200            1256.197         3.003056
  14        1270.500            1268.164         2.335723
  15        1280.000            1280.132        -.1316130
  16        1287.400            1286.115         1.284713
  17        1290.000            1292.099        -2.098949
  18        1303.000            1304.066        -1.066285
  19        1314.400            1316.034        -1.633628
```

For P = 350 psia

a = 942.15142 b = 0.61678 $R^2 = 0.99710$

F = 3091.46246

```
            OBSERVED            PREDICTED
SEQNUM        H09                  H09              RESIDUAL
   9        1210.300            1213.536           -3.236487
  10        1220.000            1219.704             .2956833
  11        1224.800            1225.872           -1.072171
  12        1239.500            1238.208            1.292157
  13        1252.900            1250.544            2.356467
  14        1265.000            1262.879            2.120789
  15        1276.000            1275.215             .7851047
  16        1282.900            1281.383            1.517257
  17        1287.000            1287.551           -.5505794
  18        1298.000            1299.886           -1.886264
  19        1310.600            1312.222           -1.621957
```

For P = 400 psia

a = 909.59054 b = 0.66861 $R^2 = 0.99431$

F = 1398.75874

```
            OBSERVED            PREDICTED
SEQNUM        H10                  H10              RESIDUAL
  10        1206.000            1210.463           -4.463164
  11        1216.500            1217.149           -.6492221
  12        1231.600            1230.521            1.078652
  13        1245.900            1243.893            2.006539
  14        1259.900            1257.266            2.634422
  15        1272.400            1270.638            1.762306
  16        1280.000            1277.324            2.676254
  17        1284.300            1284.010             .2901833
  18        1295.800            1297.382           -1.581933
  19        1307.000            1310.754           -3.754037
```

For P = 450 psia

a = 895.53893 b = 0.68510 R^2 = 0.99481

F = 1340.50940

```
             OBSERVED         PREDICTED
SEQNUM         H11               H11          RESIDUAL
  11         1207.900          1210.725      -2.825326
  12         1223.700          1224.429      -.7290788
  13         1238.700          1238.133       .5671652
  14         1253.800          1251.837      1.963400
  15         1266.900          1265.540      1.359650
  16         1276.000          1272.392      3.607778
  17         1280.000          1279.244       .7559002
  18         1291.800          1292.948      -1.147868
  19         1303.100          1306.652      -3.551621
```

For P = 500 psia

a = 880.77386 b = 0.70157 R^2 = 0.99680

F = 1867.77644

```
             OBSERVED         PREDICTED
SEQNUM         H12               H12          RESIDUAL
  12         1215.300          1217.529      -2.228687
  13         1231.400          1231.560      -.1601313
  14         1246.600          1245.592      1.008415
  15         1261.100          1259.623      1.476964
  16         1268.000          1266.639      1.361248
  17         1275.000          1273.654      1.345523
  18         1287.300          1287.686      -.3859404
  19         1299.300          1301.717      -2.417391
```

For P = 550 psia

a = 863.46214 b = 0.72296 R^2 = 0.99813

F = 3206.29259

```
             OBSERVED         PREDICTED
SEQNUM         H13               H13          RESIDUAL
  12         1210.000          1210.481      -.4813924
  13         1223.400          1224.941      -1.540534
  14         1240.000          1239.400       .6003365
  15         1254.800          1253.859       .9411887
  16         1262.000          1261.088       .9116332
  17         1269.800          1268.318      1.482053
  18         1282.900          1282.777       .1229237
  19         1295.200          1297.236      -2.036209
```

Second the relation between pressure and a and b values of Eq. (A.1.1) is found.

$$a = 1059.76347 - 0.35437P \qquad (A.1.2)$$

with $R^2 = 0.99289$ and $F = 1535.31428$

```
SEQNUM         OBSERVED            PREDICTED         RESIDUAL

     1         1050.850            1054.556         -3.705699
     2         1048.242            1052.676         -4.433707
     3         1038.488            1042.045         -3.556818
     4         1021.793            1024.326         -2.623312
     5         1009.901            1006.607          3.293189
     6         996.9477            988.8888          8.058933
     7         980.5354            971.1701          9.365272
     8         957.0135            953.4514          3.562123
     9         942.1514            935.7327          6.418687
    10         909.5905            918.0140         -8.423510
    11         895.5389            900.2954         -4.756445
    12         880.7739            882.5767         -1.802835
    13         863.4621            864.8580         -1.395879
```

$$b = 0.46003 + 0.00048P \qquad (A.1.3)$$

with $R^2 = 0.98794$ and $F = 901.38206$

```
SEQNUM         OBSERVED            PREDICTED         RESIDUAL

     1         .4723900            .4670662          .5323833-02
     2         .4755900            .4696065          .5983481-02
     3         .4899600            .4839750          .5984987-02
     4         .5141800            .5079225          .6257491-02
     5         .5258700            .5318700         -.6000004-02
     6         .5423700            .5558175         -.1344749-01
     7         .5636700            .5797650         -.1609499-01
     8         .5983700            .6037125         -.5342487-02
     9         .6167800            .6276600         -.1087998-01
    10         .6686100            .6516075          .1700253-01
    11         .6851900            .6755550          .9635039-02
    12         .7015700            .6995025          .2067543-02
    13         .7229600            .7234499         -.4899522-03
```

As a result fitted equation for enthalpy is found by substituting Eqs. (A.1.2) and (A.1.3) into Eq. (A.1.1) which is

$$H = 1059.76347 - 0.35437P + 0.46003T + 0.00048\,PT \qquad (A.1.4)$$

Equation for enthalpy of steam came out to be linear therefore linear fitting is applied to the same data set in order to check the equation fitted and Eq. (A.1.5) is found.

$$H = 1046.2097 + 0.1950P + 0.4440T - 0.0005\,PT \qquad (A.1.5)$$

with $R^2 = 0.8570$ and $F = 131.813$.

Differences in coefficients of Eqs. (A.1.4) and (A.1.5) are calculated to be

COEFFICIENT	DIFFERENCE
constant	13.55377
P	- 0.54937
T	0.01603
PT	0.00098

A.2 CHARACTERIZATION FACTOR OF PETROLEUM FRACTIONS

Fitted equation for characterization factor, K as function of API-Gravity and kinematic viscosity (cst) at 122°F is found by using 44 points which are read from graph [27].

First API is held constant and relation between K and kinematic viscosity is found.

$$K = a\,\nu^{0.015} + b \qquad (A.2.1)$$

SEQNUM	ν
1	100
2	200
3	300
4	400
5	500
6	600
7	700
8	800
9	900
10	1000
11	2000

For API = 12.5

$$K = 8.86721\nu^{0.915} + 1.46868 \qquad \text{(A.2.1a)}$$

with $R^2 = 0.97758$ and $F = 392.42538$

```
                OBSERVED            PREDICTED
SEQNUM             K2                  K2            RESIDUAL

     1          11.00000            10.97007          .2992992-01
     2          11.05000            11.06937         -.1937346-01
     3          11.10000            11.12794         -.2794248-01
     4          11.15000            11.16971         -.1971454-01
     5          11.20000            11.20224         -.2239734-02
     6          11.25000            11.22890          .2110435-01
     7          11.25000            11.25149         -.1489914-02
     8          11.27000            11.27110         -.1104228-02
     9          11.30000            11.28844          .1156204-01
    10          11.32000            11.30397          .1603047-01
    11          11.40000            11.40676         -.6762426-02
```

For API = 15

$$K = 10.51012\ \nu^{0.015} - 0.10857 \qquad \text{(A.2.1b)}$$

with $R^2 = 0.95045$ and $F = 172.63262$

SEQNUM	OBSERVED K3	PREDICTED K3	RESIDUAL
1	11.20000	11.15323	.4677421-01
2	11.25000	11.27093	-.2092787-01
3	11.30000	11.34035	-.4034849-01
4	11.35000	11.38986	-.3986015-01
5	11.40000	11.42841	-.2841145-01
6	11.48000	11.46001	.1999369-01
7	11.50000	11.48679	.1321329-01
8	11.51000	11.51004	-.3513220-04
9	11.55000	11.53058	.1941956-01
10	11.60000	11.54899	.5101029-01
11	11.65000	11.67083	-.2082794-01

For API = 17.5

$$K = 10.85509\ \nu^{0.015} - 0.21929 \qquad \text{(A.2.1c)}$$

with $R^2 = 0.96453$ and $F = 244.70131$

SEQNUM	OBSERVED K4	PREDICTED K4	RESIDUAL
1	11.40000	11.41214	-.1214400-01
2	11.50000	11.53371	-.3370945-01
3	11.60000	11.60541	-.5408705-02
4	11.67000	11.65655	.1345461-01
5	11.75000	11.69636	.5363791-01
6	11.75000	11.72899	.2100609-01
7	11.75000	11.75665	-.6653421-02
8	11.77000	11.78066	-.1066493-01
9	11.80000	11.80188	-.1884586-02
10	11.85000	11.82090	.2910190-01
11	11.90000	11.94674	-.4673542-01

For API = 20

$$K = 11.28989\ \nu^{0.015} - 0.47232 \qquad \text{(A.2.1d)}$$

with $R^2 = 0.97624$ and $F = 369.848$

```
            OBSERVED          PREDICTED
SEQNUM         K5                K5              RESIDUAL

   1        11.62000          11.62501         -.5013825-02
   2        11.75000          11.75145         -.1448489-02
   3        11.80000          11.82602         -.2601960-01
   4        11.85000          11.87920         -.2920466-01
   5        11.95000          11.92062          .2938376-01
   6        12.00000          11.95456          .4544495-01
   7        12.00000          11.98332          .1667754-01
   8        12.01000          12.00830          .1704257-02
   9        12.03000          12.03037         -.3653389-03
  10        12.05000          12.05014         -.1404121-03
  11        12.15000          12.18102         -.3101819-01
```

Second, the relation between API and a and b values of Eq. (A.2.1) is found

$$a = -91.90768\mathrm{API} + 9.14945\mathrm{API}^2 - 0.39620\mathrm{API}^3 + 0.00632\mathrm{API}^4 + 347.56742 \qquad \text{(A.2.2)}$$

with $R^2 = 1.00000$ and $F = 2.71\times10^{11}$

```
            OBSERVED          PREDICTED
SEQNUM         A                 A               RESIDUAL
   2        8.867210          8.867210          .2080229-11
   3        10.51012          10.51012         -.2924837-11
   4        10.85509          10.85509          .1833559-11
   5        11.28989          11.28989         -.4293423-12
```

$$b = 100.73420API - 10.04215API^2 + 0.43579API^3 - 0.00697API^4 - 369.64072 \qquad (A.2.3)$$

with $R^2 = 1.00000$ and $F = 1.7\text{x}10^{11}$

```
             OBSERVED              PREDICTED
SEQNUM          B                     B                RESIDUAL
     2       1.468680              1.468680           -.2284337-11
     3      -.1085700             -.1085700            .3211480-11
     4      -.2192900             -.2192900           -.2013177-11
     5      -.4723200             -.4723200            .4727742-12
```

As a result fitted equation for K-factor is found by substituting Eqs. (A.2.3) and (A.2.2) into Eq. (A.2.1) which is

$$\begin{aligned} K = \nu^{0.015}(&-91.90768API + 9.14945API^2 - 0.39620API^3 + 0.00632API^4 \\ &+ 347.56742) + 100.73420API - 10.04215API^2 + 0.43579API^3 \\ &- 0.00697API^4 - 369.64072 \end{aligned} \qquad (A.2.4)$$

A.3 MOLECULAR WEIGHT OF PETROLEUM FRACTIONS

Fitted equation for molecular weight as function of API and K-factor is found by using 24 points which are read from graph [27].

First API is held constant and relation between molecular weight and K is found.

$$MW = b\, e^{aK} \qquad (A.3.1)$$

$$\text{Ln } MW = \ln b + aK \qquad (A.3.1a)$$

For API = 10

$$\text{Ln } MW = -2.50757 + 0.77146\, K \qquad (A.3.1b)$$

with $R^2 = 0.99956$ and $F = 4586.247$

```
SEQNUM        OBSERVED              PREDICTED
                LNY                    LNY           RESIDUAL

   1          5.214936              5.207019         .7917029E-02
   2          5.579730              5.592748        -.1301827E-01
   3          5.978886              5.978477         .4082647E-03
   4          6.214608              6.209915         .4692978E-02
```

For API = 20

$$\text{Ln MW} = -2.70190 + 0.74984\ K \tag{A.3.1c}$$

with $R^2 = 0.99800$ and $F = 995.873$

```
SEQNUM        OBSERVED              PREDICTED
                LNY                    LNY           RESIDUAL

   1          4.820282              4.796468         .2381346E-01
   2          5.501258              5.546305        -.4504642E-01
   3          6.291569              6.296141        -.4572012E-02
   4          6.396930              6.371125         .2580498E-01
```

For API = 30

$$\text{Ln MW} = -2.65563 + 0.71041\ K \tag{A.3.1d}$$

with $R^2 = 0.99709$ and $F = 684.417$

```
SEQNUM        OBSERVED              PREDICTED
                LNY                    LNY           RESIDUAL

   1          4.488636              4.448503         .4013372E-01
   2          5.099866              5.158916        -.5904938E-01
   3          5.857933              5.869329        -.1139584E-01
   4          6.396930              6.366618         .3031151E-01
```

For API = 40

$$\text{Ln MW} = -2.69444 + 0.67681\ K \tag{A.3.1e}$$

with $R^2 = 0.99891$ and $F = 1831.978$

```
SEQNUM        OBSERVED              PREDICTED
                LNY                    LNY           RESIDUAL

   1          4.094345              4.073638         .2070654E-01
   2          4.736198              4.750445        -.1424708E-01
   3          5.393628              5.427253        -.3362547E-01
   4          6.131226              6.104060         .2716600E-01
```

For API = 60

$$\text{Ln MW} = -2.31104 + 0.58297\ K \qquad \text{(A.3.1f)}$$

with $R^2 = 0.99998$ and $F = 101520.894$

```
                 OBSERVED                PREDICTED
SEQNUM             LNY                      LNY
                                                          RESIDUAL
    1            4.394449                4.393069        .1380515-02
    2            4.682131                4.684552       -.2420372-02
    3            4.976734                4.976035        .6991982-03
    4            5.267858                5.267517        .3406584-03
```

For API = 80

$$\text{Ln MW} = -2.52526 + 0.55088\ K \qquad \text{(A.3.1g)}$$

with $R^2 = 0.99497$ and $F = 395.440$

```
                 OBSERVED                PREDICTED
SEQNUM             LNY                      LNY
                                                          RESIDUAL
    1            4.248495                4.250560       -.2064862-02
    2            4.356709                4.360736       -.4027180-02
    3            4.543295                4.526000        .1729497-01
    4            4.624973                4.636176       -.1120292-01
```

Second, the relation between API and a and b values of Eq. (A.3.1) is found

$$a = 33.14991 \cos(\text{API}/120) + 0.00107\ \text{API}^2 - 32.37074 \qquad \text{(A.3.2)}$$

with $R^2 = 0.99882$ and $F = 1268.83780$

```
                 OBSERVED                PREDICTED
SEQNUM              Y                        Y
                                                          RESIDUAL
    1             .7714600               .7714539         .6044558-05
    2             .7498400               .7491320         .7080410-03
    3             .7104100               .7145846        -.4174558-02
    4             .6768100               .6717759         .5034120-02
    5             .5829700               .5849307        -.1960727-02
    6             .5508800               .5504929         .3870789-03
```

$$b = 0.20814 - 10^{-5}\text{API}(-2391.699992 + 150.66076\ \text{API} - 4.37442\ \text{API}^2 + 0.05865\ \text{API}^3 - 0.00029\ \text{API}^4) \qquad \text{(A.3.3)}$$

with $R^2 = 1.00000$ and $F = 8.96 \times 10^{10}$

```
           OBSERVED              PREDICTED
SEQNUM        Y                      Y
                                                   RESIDUAL
   1      .8146600-01           .8146600-01       .3277014-13
   2      .6707800-01           .6707800-01     -.1350746-12
   3      .7025500-01           .7025500-01       .2027725-12
   4      .6758000-01           .6758000-01     -.1186157-12
   5      .9915700-01           .9915700-01       .2061828-13
   6      .8084200-01           .8084200-01     -.2544122-14
```

As a result fitted equation for molecular weight is found by substituting Eqs. (A.3.3) and (A.3.2) into Eq. (A.3.1) which is

$$\begin{aligned} MW = {} & [0.20814 - 10^{-5}\text{API}(-2391.69992 + 150.66076\ \text{API}^2 \\ & - 4.37442\ \text{API}^3 + 0.05865\ \text{API}^4 - 0.00029\ \text{API}\ )] * \\ & \exp[[33.14991 \cos(\text{API}/120) + 0.00107\ \text{API}^2 \\ & - 32.37074]K] \end{aligned} \qquad \text{(A.3.4)}$$

A.4 GAS PHASE THERMAL CONDUCTIVITY OF PETROLEUM FRACTIONS

Fitted equation for thermal conductivity (Btu/hr-ft-°F) as function of molecular weight and temperature (°F) is found by using 27 points which are read from graph [27].

First molecular weight is held constant and relation between thermal conductivity and temperature is found. Because the relation observed from graph is linear the slope and intercept is found by using Least Square Method.

$$k_g = aT + b \qquad \text{(A.4.1)}$$

Temperature values used in fitting are 300, 500 and 700.

MW	$a \times 10^5$	$b \times 10^2$
15	5.35	1.1625
20	4.75	1.17
25	4.1	1.06
30	3.6	1.057
44	3.225	0.744
50	3.05	0.688
75	2.825	0.684
100	2.675	0.626
150	2.675	0.186

Second, the relations between temperature and a and b values of Eq. (A.4.1) are found.

$$a = 0.0379 \times 10^{-5} MW + 0.00026\ MW^{-0.31342} - 1 \times 10^{-9} MW^2 - 6 \times 10^{-5} \qquad (A.4.2)$$

with $R^2 = 0.99343$ and $F = 252.13069$

```
               OBSERVED                  PREDICTED
SEQNUM            Y                          Y              RESIDUAL

     1         .5350000-04              .5394093-04       -.4409346-06
     2         .4750000-04              .4617886-04        .1321136-05
     3         .4100000-04              .4106240-04       -.6240295-07
     4         .3600000-04              .3748091-04       -.1480909-05
     5         .3225000-04              .3175473-04        .4952677-06
     6         .3050000-04              .3039075-04        .1092523-06
     7         .2825000-04              .2779219-04        .4578136-06
     8         .2675000-04              .2723943-04       -.4894344-06
     9         .2675000-04              .2665979-04        .9021109-07
```

$$b = 0.11260\ MW^{-0.47367} - 0.00574\ \sin(MW^{0.3}) - 0.01092 \quad (A.4.3)$$

```
             OBSERVED              PREDICTED
SEQNUM         Y                     Y                RESIDUAL

   1        .1625000-01          .1584245-01        .4075459-03
   2        .1170000-01          .1268763-01       -.9876341-03
   3        .1060000-01          .1076020-01       -.1601962-03
   4        .1057000-01          .9498420-02        .1071579-02
   5        .7440000-02          .7661204-02       -.2212040-03
   6        .6880000-02          .7257386-02       -.3773858-03
   7        .6840000-02          .6450491-02        .3895095-03
   8        .6260000-02          .6064324-02        .1956761-03
   9        .4860000-02          .5177891-02       -.3178908-03
```

As a result fitted equation for thermal conductivity is found by substituting Eqs. (A.4.2) and (A.4.3) into Eq. (A.4.1) which is

$$\begin{aligned} k_g = {} & T(3.79\times10^{-7}MW + 2.6\times10^{-4}MW^{-0.31342} - 10^{-9}MW^2 - 6\times10^{-5}) \\ & + 0.11260\ MW^{-0.47367} - 0.00574\ \sin(MW^{0.3}) \\ & - 0.01092 \end{aligned} \quad (A.4.4)$$

A.5 CRITICAL PRESSURE OF PETROLEUM FRACTIONS

Fitted equation for critical pressure (psi) as function of boiling temperature (°F) and critical temperature (°F) is found by using 35 points which are read from graph [30].

First boiling temperature is held constant and relation between critical pressure and critical temperature is found.

$$P_c = b\ T_c^a \quad (A.5.1)$$

$$\mathrm{Ln}\ P_c = \mathrm{Ln}\ b + a\ \mathrm{Ln}\ T_c \quad (A.5.1a)$$

T_B	Ln b	a	R^2	F
300	-22.52840	4.41385	0.99843	1903.508
400	-25.39992	4.72134	0.99906	3180.025
500	-29.40876	5.19750	0.99879	2486.337
600	-30.96287	5.31485	0.99853	2032.965
700	-34.27820	5.69150	0.99891	2759.281
800	-40.98465	6.54862	0.99793	1447.452
900	-45.91711	7.15464	0.99895	2843.044

Second the relations between boiling temperature and a and ln b values of Eq. (A.5.1a) are found.

$$a = 4.09625 + 0.37036\text{x}10^{-5}T_B^2 \qquad \text{(A.5.2)}$$

with $R^2 = 0.98195$ and $F = 272.065$

$$\text{Ln } b = -20.13179 - 3\text{x}10^{-5}T_B \qquad \text{(A.5.3)}$$

with $R^2 = 0.98881$ and $F = 441.97195$

As a result fitted equation for critical pressure is found by substituting Eqs. (A.5.3) and (A.5.2) into Eq. (A.5.1) which is

$$P_c = [\exp(-20.13179 - 3\text{x}10^{-5}T_B)]T_c^{(4.09629+3.7036\text{x}10^{-6}T_B{}^2)} \qquad \text{(A.5.4)}$$

A.6 BOILING POINT OF PETROLEUM FRACTIONS BELOW ATMOSPHERIC PRESSURE

Fitted equation for boiling temperature (°F) below atmospheric pressure as function of boiling temperature (°F) at atmospheric pressure and pressure (mm Hg) is found by using 21 points which are read from graph [39].

First, pressure is held constant and relation between boiling temperatures at atmospheric pressure (T_B) and at that fixed pressure T'_B is found.

Because the relation seen from the graph is linear, the slope and intercept is found by using Least square method.

$$T_B = aT'_B + b \tag{A.6.1}$$

T_B values used are 400, 600 and 800.

P	a	b
100	1.1111	94.4444
200	1.0667	69.1568
300	1.0390	49.6982
400	1.0256	35.8974
500	1.023	21.3144
600	1.0000	18.0000
760	1.0000	0.0000

Second, the relation between pressure and a and b values of Eq. (A.6.1) are found.

$$a = 0.99316 + 0.12906 \log(760/P) \tag{A.6.2}$$

with $R^2 = 0.97880$ and $F = 230.898$

$$b = 106.46313 \log(760/P) + 4.29520 \tag{A.6.3}$$

with $R^2 = 0.98989$ and $F = 489.477$

As a result fitted equation for boiling temperature below atmospheric pressure is found by substituting Eqs. (A.6.2) and (A.6.3) into Eq. (A.6.1) and rearranging for T_B' which is

$$T_B' = \frac{T_B - [106.46313 \log(760/P) + 4.29520]}{0.99316 + 0.12906 \log(760/P)}$$

A.7 CONVECTIVE HEAT TRANSFER CORRECTION FACTOR IN CHEN CORRELATION

Fitted equation for convective heat transfer correction factor in Chen correlation as function of Lockhart-Martinelli parameter is found by using 6 points which are read from graph [35].

The relation is reached by a computer program which uses Least square method.

$$F_c = 0.862888 + \frac{1.426638}{X_{tt}} + \frac{0.074524}{X_{tt}^2} - \frac{0.011958}{X_{tt}^3}$$

$1/X_{tt}$	Observed F_c	Predicted F_c	% Error
.1000000000	1.000000000	1.005552207519536	-0.5552207519535557
.2000000000	1.100000000	1.148216045802229	-4.383276891111749
.5000000000	1.700000000	1.576207560650310	7.281908197040570
1.000000000	2.300000000	2.289526752063779	0.4553586059226622
4.000000000	7.000000000	6.569441900544589	6.150829992220151
6.500000000	10.00000000	10.13603785761193	-1.360378576119317

A.8 NUCLEATE-BOILING SUPPRESSION FACTOR IN CHEN CORRELATION

Fitted equation for nucleate-boiling suppression factor in Chen correlation as function of two phase Reynolds number is found by using 5 points which are read from graph [35].

The relation is reached by a computer program which uses Least square method.

$$S_c = -0.4669855 + 17.62527375 \quad Re_{tp}^{-0.265}$$

$Re_{tp}^{-0.265}$	Observed S_c	Calculated S_c	% Error
7.2481479754125736E-02	0.794000000000000	0.8105177526706288	-2.080321495041405
5.6855560964712932E-02	0.571000000000000	0.5351072235112429	6.285950348293711
4.7315125896148049E-02	0.366000000000000	0.3669547899772558	-0.2608715784851936
3.9375587903490892E-02	0.200000000000000	0.2270185475516080	-13.50927377580398
3.0886802341268546E-02	8.600000000000000E-02	7.7401686289265137E-02	9.998039198528911

APPENDIX B

INTEGRATION OF THE RADIATION ANGLE FACTOR

Integration of radiation angle factor (Equation (3.73)) from flame to each tube is shown in this chapter.

$$F_{A_i-A_j} = \frac{1}{\pi L_f b} \int_{0}^{b} \int_{0}^{L_f} \int_{0}^{b} \int_{(s-1)a}^{sa} \frac{y_i^2 dz_j dx_j dz_i dx_i}{[(x_i-x_j)^2+y_i^2+(z_i-z_j)^2]^2} \qquad (B.1)$$

Equation (B.1) is first integrated with respect to z_j

$$\text{-----} \int_{(s-1)a}^{sa} \frac{y_i^2 dz_j}{[(x_i-x_j)^2+y_i^2+(z_i-z_j)^2]^2} \qquad (B.1a)$$

setting $c = y_i^2$, and $K = (x_i-x_j)^2 + y_i^2$

$$\text{-----} -\int_{(s-1)a}^{sa} \frac{-c^2 dz_j}{[K + (z_i-z_j)^2]^2} \qquad (B.1b)$$

Letting $z = z_i-z_j$ then $dz = -dz_j$

$$\text{-----} -c^2 \int_{z_1}^{z_2} \frac{dz}{(K + z^2)^2}$$

from integration table [40] the integral is found to be

$$------ - \frac{c^2}{2K}\Bigg|_{z_1}^{z_2} \left\{\frac{z}{K + z^2} + \frac{1}{\sqrt{K}} \tan^{-1} \frac{z}{\sqrt{K}}\right\} \qquad (B.2)$$

$$------ - \frac{c^2}{2K}\Bigg|_{(s-1)a}^{sa} \left\{\frac{z_i - z_j}{K + (z_i-z_j)^2} + \frac{1}{\sqrt{K}} \tan^{-1} \frac{z_i-z_j}{\sqrt{K}}\right\} \qquad (B.2a)$$

Substituting and rearranging gives

$$F_{A_i-A_j} = \frac{-c^2}{2\pi b L_f} \int_0^b \int_0^{L_f} \int_0^b \frac{dx_j dz_i dx_i}{(x_i - x_j)^2 + c^2} \left\{\frac{z_i - sa}{(x_i-x_j)^2 + c^2 + (z_i-sa)^2}\right.$$

$$- \frac{z_i - (s-1)a}{(x_i-x_j)^2 + c^2 + (z_i-(s-1)a)^2}$$

$$+ \frac{1}{((x_i-x_j)^2+c^2)^{1/2}} \left[\tan^{-1} \frac{z_i - sa}{((x_i-x_j)^2+c^2)^{1/2}}\right.$$

$$\left.\left.- \tan^{-1} \frac{z_i - (s-1)a}{((x_i-x_j)^2 + c^2)^{1/2}}\right]\right\} \qquad (B.2b)$$

Then Eq. (B.2b) is integrated with respect to x_j. Setting

$L_3 = c^2 + (z_i-sa)^2$, $L_4 = c^2 + [z_i - (s-1)a]^2$,

$L_5 = z_i - sa$, and $L_6 = z_i - (s-1)a$

$$---- \int_{o}^{b} \frac{dx_j}{(x_i-x_j)^2+c^2} \left[\frac{L_5}{(x_i-x_j)^2+L_3} - \frac{L_6}{(x_i-x_j)^2+L_4} \right]$$

$$+ \int_{o}^{b} \frac{dx_j}{((x_i-x_j)^2+c^2)^{3/2}} \left[\tan^{-1} \frac{L_5}{((x_i-x_j)^2+c^2)^{1/2}} - \tan^{-1} \frac{L_6}{((x_i-x_j)^2+c^2)^{1/}}\right.$$

(B.2c)

Letting $x = x_i-x_j$ then $dx = -dx_j$

$$------ -\int_{x_1}^{x_2} \frac{dx}{x^2+c^2} \left[\frac{L_5}{x^2+L_3} - \frac{L_6}{x^2+L_4}\right]$$

$$- \int_{x_1}^{x_2} \frac{dx}{(x^2+c^2)^{3/2}} \left[\tan^{-1} \frac{L_5}{(x^2+c^2)^{1/2}} - \tan^{-1} \frac{L_6}{(x^2+c^2)^{1/2}}\right]$$

(B.2d)

The first integral of Eq. (B.2d) is evaluated with the aid of partial fraction expansion and it is found to be

$$\frac{1}{c} [\tan^{-1}((x_i-b)/c) - \tan^{-1}(x_i/c)][(L_6/(L_4-c^2)) - (L_5/(L_3-c^2))]$$

$$+ [\tan^{-1}((x_i-b)/\sqrt{L_3}) - \tan^{-1}(x_i/\sqrt{L_3})][L_5/(\sqrt{L_3}(L_3-c^2))]$$

$$- [\tan^{-1}((x_i-b)/\sqrt{L_4}) - \tan^{-1}(x_i/\sqrt{L_4})][L_6/(\sqrt{L_4}(L_4-c^2))] \qquad (B.3)$$

The second integral of Eq. (B.2d) is evaluated in two steps. First by the method of integration by parts. Letting $du = dx/(x^2+c^2)^{3/2}$ and $v = \tan^{-1}(L/(x^2+c^2)^{1/2})$. Then from integral table [40]

$$u = \frac{x}{c^2(x^2 + c^2)^{1/2}}$$

$$dv = \frac{x^2 + c^2}{x^2 + c^2 + L^2} \cdot \frac{-x\ L\ dx}{(x^2 + c^2)^{3/2}}$$

The integral is equal to $uv - \int udv$.

Then the resulting integral after first evaluation after rearranging is

$$\begin{aligned}
&\Big|_{x_1}^{x_2} \{(x/(c^2(x^2+c^2)^{1/2}))[\tan^{-1}(L_6/(x^2+c^2)^{1/2}) - \tan^{-1}(L_5/(x^2+c^2)^{1/2})]\} \\
&- \int_{x_1}^{x_2} (x^2 L_5 dx)/(c^2(x^2+c^2)(x^2+c^2+L_5^2)) + \int_{x_1}^{x_2} (x^2 L_6 dx)/(c^2(x^2+c^2)(x^2+c^2+L_6^2)) \qquad \text{(B.4)}
\end{aligned}$$

The second step is the evaluation of two integrals of Eq. (B.4) by the aid of partial fraction expansion then the result of Eq. (B.4) is

$$\begin{aligned}
&((x_i-b)/(c^2((x_i-b)^2+c^2)^{1/2}))[\tan^{-1}(L_6/((x_i-b)^2+c^2)^{1/2}) \\
&- \tan^{-1}(L_5/((x_i-b)^2+c^2)^{1/2})] - (x_i/(c^2(x_i^2+c^2)^{1/2}))[\tan^{-1}(L_6/(x_i^2+c^2)^{1/2}) \\
&- \tan^{-1}(L_5/(x_i^2+c^2)^{1/2})] - (1/c^2)[((L_5-L_6)c\ /(L_5L_6))(\tan^{-1}((x_i-b)/c) \\
&- \tan^{-1}(x_i/c)) + ((c^2+L_5^2)^{1/2}/L_5)(\tan^{-1}((x_i-b)/(c^2+L_5^2)^{1/2}) \\
&- \tan^{-1}(x_i/(c^2+L_5^2)^{1/2})) - ((c^2+L_6^2)^{1/2}/L_6)(\tan^{-1}((x_i-b)/((c^2+L_6^2)^{1/2})) \\
&- \tan^{-1}(x_i/(c^2+L_6^2)^{1/2}))] \qquad \text{(B.5)}
\end{aligned}$$

Addition of Eqs. (B.3) and (B.5) gives the result of integration of Eq. (B.2b) with respect to x_j. After back substitution and rearranging it is found to be

$$F_{A_i-A_j} = \frac{-1}{2\pi b L_f} \int_0^b \int_0^{L_f} dz_i dx_i \{\frac{x_i - b}{((x_i-b)^2+c^2)^{1/2}} [\tan^{-1}(\frac{z_i -(s-1)a}{((x_i-b)^2+c^2)^{1/2}})$$

$$- \tan^{-1}(\frac{z_i - sa}{((x_i-b)^2+c^2)^{1/2}})] - \frac{x_i}{(x_i^2+c^2)^{1/2}}[\tan^{-1}(\frac{(z_i-(s-1)a)}{(x_i^2+c^2)^{1/2}})$$

$$- \tan^{-1}(\frac{z_i-sa}{(x_i^2+c^2)^{1/2}})] + \frac{z_i - (s-1)a}{(c^2 + (z_i-(s-1)a)^2)^{1/2}} *$$

$$[\tan^{-1}(\frac{x_i - b}{(c^2+(z_i-(s-1)a)^2)^{1/2}}) - \tan^{-1} \frac{x_i}{(c^2+(z_i-(s-1)a)^2)^{1/2}}]$$

$$- \frac{z_i - sa}{(c^2+(z_i-sa)^2)^{1/2}} [\tan^{-1}(\frac{x_i - b}{(c^2+(z_i-sa)^2)^{1/2}})$$

$$- \tan^{-1}(\frac{x_i}{(c^2+(z_i-sa)^2)^{1/2}})]\} \qquad \text{(B.6)}$$

Then Eq. (B.6) is integrated with respect to dz_i setting

$A = sa$, $A_1 = (s-1)a$

$M = x_i-b$, $M_1 = ((x_i-b)^2+c^2)^{1/2}$, $M_2 = (x_i^2+c^2)^{1/2}$

$$----- M \int_0^{L_f} (\tan^{-1}((z_i-A)/M_1) - \tan^{-1}((z_i-A_1)/M_1)) (dz_i/M_1)$$

$$- x_i \int_0^{L_f} (\tan^{-1}((z_i-A)/M_2) - \tan^{-1}((z_i-A_1)/M_2)) (dz_i/M_2)$$

$$+ \int_0^{L_f} ((z_i-A)/((c^2+(z_i-A)^2)^{1/2}))[\tan^{-1}(M/((c^2+(z_i-A)^2)^{1/2}))$$

$$- \tan^{-1}(x_i/((c^2+(z_i-A)^2)^{1/2}))]dz_i - \int_0^{L_f} ((z_i-A_1)/((c^2+(z_i-A_1)^2)^{1/2})) *$$

$$[\tan^{-1}(M/((c^2+(z_i-A_1)^2)^{1/2})) - \tan^{-1}(x_i/((c^2+(z_i-A_1)^2)^{1/2}))]dz_i$$

$$\text{(B.6a)}$$

First two integrals of Eq. (B.6a) are evaluated by substitution method.

Letting $x = \dfrac{z_i - A'}{M'}$ $\qquad dx = \dfrac{dz_i}{M'}$

Then the integral is from tables [40]

$$\int \tan^{-1} x \, dx = x \tan^{-1} x - (1/2)\ln(1 + x^2)$$

The result after evaluation is

$$\begin{aligned}
&(M/M_1)[(L_f-A)\tan^{-1}((L_f-A)/M_1) + \tan^{-1}(-A/M_1) - (L_f-A_1)\tan^{-1}((L_f-A_1)/M_1) \\
&\quad - A_1\tan^{-1}(-A_1/M_1)] - (x_i/M_2)[(L_f-A)\tan^{-1}((L_f-A)/M_2) \\
&\quad + A\tan^{-1}(-A/M_2) - (L_f-A_1)\tan^{-1}((L_f-A_1)/M_2) - A_1\tan^{-1}(-A_1/M_2)] \\
&\quad +(M/2)\ln(((M_1^2+A^2)/(M_1^2+(L_f-A)^2))((M_1^2+(L_f-A_1)^2)/(M_1^2+A_1^2))) \\
&\quad +(x_i/2)\ln(((M_2^2+(L_f-A)^2)/(M_2^2+A^2))((M_2^2+A_1^2)/(M_2^2+(L_f-A_1)^2))) \quad (B.7)
\end{aligned}$$

The third and fourth integrals of Eq. (B.6a) are evaluated by substitution method in two steps.

First $z = z_i - A'$ $\qquad$ then $\qquad dz = dz_i$

second $\qquad u = (c^2+z^2)^{-1/2}$ $\qquad$ then $\qquad du = -zdz/(c^2+z^2)^{3/2}$

Resulting integral has the form

$$-\int_{u_1}^{u_2} (du/u^2)\tan^{-1}u \, M'$$

From tables [40] the solution is

$$\Big|_{u_1}^{u_2}[(1/u)\tan^{-1}M'u - (M'/2)\ln(u\;/(1+M'^2u^2))]$$

Accordingly the result of third integral is

$$\begin{aligned}&(c^2+(L_f-A)^2)^{1/2}[\tan^{-1}\frac{M}{(c^2+(L_f-A)^2)^{1/2}} - \tan^{-1}\frac{x_i}{(c^2+(L_f-A)^2)^{1/2}}]\\ &- (c^2+A^2)^{1/2}[\tan^{-1}\frac{M}{(c^2+A^2)^{1/2}} - \tan^{-1}\frac{x_i}{(c^2+A^2)^{1/2}}]\\ &- \frac{M}{2}\ln\frac{c^2+A^2+M^2}{c^2+(L_f-A)^2+M^2} + \frac{x_i}{2}\ln\frac{c^2+A^2+x_i^2}{c^2+(L_f-A)^2+x_i^2}\end{aligned} \qquad (B.8)$$

The result of the fourth integral is

$$\begin{aligned}&-(c^2+(L_f-A_1)^2)^{1/2}[\tan^{-1}\frac{M}{(c^2+(L_f-A_1)^2)^{1/2}} - \tan^{-1}\frac{x_i}{(c^2+(L_f-A_1)^2)^{1/2}}]\\ &+ (c^2+A_1^2)^{1/2}[\tan^{-1}\frac{M}{(c^2+A_1^2)^{1/2}} - \tan^{-1}\frac{x_i}{(c^2+A_1^2)^{1/2}}]\\ &+ \frac{M}{2}\ln\frac{c^2+A_1^2+M^2}{c^2+(L_f-A_1)^2+M^2} - \frac{x_i}{2}\ln\frac{c^2+A_1^2+x_i^2}{c^2+(L_f-A_1)^2+x_i^2}\end{aligned} \qquad (B.9)$$

Addition of Eqs. (B.7), (B.8) and (B.9) gives the result of integration of Eq. (B.6) with respect to z_i. After back substitution and rearranging it is found to be

$$
\begin{aligned}
F_{A_i-A_j} = \frac{1}{2\pi bL_f}\int_0^b dx_i\{&\frac{x_i-b}{((x_i-b)^2+c^2)^{1/2}}[(L_f-sa)\tan^{-1}\frac{L_f-sa}{((x_i-b)^2+c^2)^{1/2}} \\
&+ sa\tan^{-1}\frac{-sa}{((x_i-b)^2+c^2)^{1/2}} - (L_f-(s-1)a)\tan^{-1}\frac{L_f-(s-1)a}{((x_i-b)^2+c^2)^{1/2}} \\
&- (s-1)a\tan^{-1}\frac{-(s-1)a}{((x_i-b)^2+c^2)^{1/2}}] - \frac{x_i}{(x_i^2+c^2)^{1/2}}[(L_f-sa)\tan^{-1}\frac{L_f-sa}{(x_i^2+c^2)^{1/2}} \\
&+ sa\tan^{-1}\frac{-sa}{(x_i^2+c^2)^{1/2}} - (L_f-(s-1)a)\tan^{-1}\frac{L_f-(s-1)a}{(x_i^2+c^2)^{1/2}} \\
&+ (s-1)a\tan^{-1}\frac{-(s-1)a}{(x_i^2+c^2)^{1/2}}] + (c^2+(L_f-sa)^2)^{1/2}[\tan^{-1}\frac{x_i-b}{(c^2+(L_f-sa)^2)^{1/2}} \\
&- \tan^{-1}\frac{x_i}{(c^2+(L_f-sa)^2)^{1/2}}] - (c^2+s^2a^2)^{1/2}[\tan^{-1}\frac{x_i-b}{(c^2+s^2a^2)^{1/2}} \\
&- \tan^{-1}\frac{x_i}{(c^2+s^2a^2)^{1/2}}] - (c^2+(L_f-(s-1)a^2))^{1/2}[\tan^{-1}\frac{x_i-b}{(c^2+(L_f-(s-1)a)^2)^{1/2}} \\
&- \tan^{-1}\frac{x_i}{(c^2+(L_f-(s-1)a)^2)^{1/2}}] \\
&+ (c^2+(s-1)^2a^2)^{1/2}[\tan^{-1}\frac{x_i-b}{(c^2+(s-1)^2a^2)^{1/2}} - \tan^{-1}\frac{x_i}{(c^2+(s-1)^2a^2)^{1/2}}]\}
\end{aligned}
\tag{B.10}
$$

The equation (B.10) is integrated with respect to x_i setting

$A = sa$ $\qquad A_1 = (s-1)a$

$A_2 = L_f - sa$ $\qquad A_3 = L_f - (s-1)a$

$A_4 = (c^2+s^2a^2)^{1/2}$ $\qquad A_5 = (c^2+(s-1)^2a^2)^{1/2}$

$A_6 = (c^2+(L_f-sa)^2)^{1/2}$ $\qquad A_7 = (c^2+(L_f-(s-1)a)^2)^{1/2}$

$$\begin{aligned}
F_{A_i-A_j} = \frac{1}{2\pi bL_f}\int_o^b dx_i\Big\{&\frac{x_i-b}{((x_i-b)^2+c^2)^{1/2}}\Big[A_2\tan^{-1}\frac{A_2}{((x_i-b)^2+c^2)^{1/2}} \\
&+ A\tan^{-1}\frac{-A}{((x_i-b)^2+c^2)^{1/2}} - A_3\tan^{-1}\frac{A_3}{((x_i-b)^2+c^2)^{1/2}} \\
&- A_1\tan^{-1}\frac{-A_1}{((x_i-b)^2+c^2)^{1/2}}\Big] - \frac{x_i}{(x_i^2+c^2)^{1/2}}\Big[A_2\tan^{-1}\frac{A_2}{(x_i^2+c^2)^{1/2}} \\
&+ A\tan^{-1}\frac{A}{(x_i^2+c^2)^{1/2}} - A_3\tan^{-1}\frac{A_3}{(x_i^2+c^2)^{1/2}} - A_1\tan^{-1}\frac{-A_1}{(x_i^2+c^2)^{1/2}}\Big] \\
&+ A_6\Big[\tan^{-1}\frac{x_i-b}{A_6} - \tan^{-1}\frac{x_i}{A_6}\Big] - A_4\Big[\tan^{-1}\frac{x_i-b}{A_4} - \tan^{-1}\frac{x_i}{A_4}\Big] \\
&- A_7\Big[\tan^{-1}\frac{x_i-b}{A_7} - \tan^{-1}\frac{x_i}{A_7}\Big] + A_5\Big[\tan^{-1}\frac{x_i-b}{A_5} - \tan^{-1}\frac{x_i}{A_5}\Big]\Big\}
\end{aligned} \tag{B.10a}$$

For the last four terms of Eq. (B.10a)

Let $x = (x_i-b)/A'$ or x_i/A' $\qquad dx = x_i/A'$

$$\int\tan^{-1}x\,dx = x\tan^{-1}x - (1/2)\ln(1+x^2)$$

evaluation gives

$$\Big|_{o}^{b} \{A_6^2[\frac{x_i - b}{A_6} \tan^{-1} \frac{x_i - b}{A_6} - \frac{1}{2} \ln \frac{A_6^2 + (x_i - b)^2}{A_6^2 + x_i^2} - \frac{x_i}{A_6} \tan^{-1} \frac{x_i}{A_6}]$$

$$- A_4^2[\frac{x_i - b}{A_4} \tan^{-1} \frac{x_i - b}{A_4} - \frac{1}{2} \ln \frac{A_4^2 + (x_i - b)^2}{A_4^2 + x_i^2} - \frac{x_i}{A_4} \tan^{-1} \frac{x_i}{A_4}]$$

$$- A_7^2[\frac{x_i - b}{A_7} \tan^{-1} \frac{x_i - b}{A_7} - \frac{1}{2} \ln \frac{A_7^2 + (x_i - b)^2}{A_7^2 + x_i^2} - \frac{x_i}{A_7} \tan^{-1} \frac{x_i}{A_7}]$$

$$+ A_5^2[\frac{x_i - b}{A_5} \tan^{-1} \frac{x_i - b}{A_5} - \frac{1}{2} \ln \frac{A_5^2 + (x_i - b)^2}{A_5^2 + x_i^2} - \frac{x_i}{A_5} \tan^{-1} \frac{x_i}{A_5}]\} \tag{B.11}$$

For the first two terms of Eq. (B.10a)

Let $x = x_i - b$ $dx = dx_i$

$$\int_{x_1}^{x_2} \frac{xA'dx}{(x^2+c^2)^{1/2}} [\tan^{-1} \frac{A'}{(x^2+c^2)^{1/2}}]$$

Applying substitution method

$$u = (x^2+c^2)^{-1/2} \qquad du = -x(x^2+c^2)^{-3/2}dx$$

which has the same form of third and fourth integrals of Eq. (B.6a). Similarly the result of first term is found to be

$$\begin{aligned}
\Big|_{o}^{b} & \{((x_i-b)^2+c^2)^{1/2}[A_2\tan^{-1}\frac{A_2}{((x_i-b)^2+c^2)^{1/2}} + A\tan^{-1}\frac{-A}{((x_i-b)^2+c^2)^{1/2}} \\
& - A_1\tan^{-1}\frac{-A_1}{((x_i-b)^2+c^2)^{1/2}} - A_3\tan^{-1}\frac{A_3}{((x_i-b)^2+c^2)^{1/2}}] \\
& + \frac{1}{2}[-A_2^2\ln\frac{1}{(x_i-b)^2+c^2+A_2^2} + A^2\ln\frac{1}{(x_i-b)^2+c^2+A^2} \\
& - A_1^2\ln\frac{1}{(x_i-b)^2+c^2+A_1^2} + A_3^2\ln\frac{1}{(x_i-b)^2+c^2+A_3^2}]\} \qquad \text{(B.12)}
\end{aligned}$$

The result of the second term is

$$\begin{aligned}
= \Big|_{o}^{b} & \{-(x_i^2+c^2)^{1/2}[A_2\tan^{-1}\frac{A_2}{(x_i^2+c^2)^{1/2}} + A\tan^{-1}\frac{-A}{(x_i^2+c^2)^{1/2}} \\
& - A_1\tan^{-1}\frac{-A_1}{(x_i^2+c^2)^{1/2}} - A_3\tan^{-1}\frac{A_3}{(x_i^2+c^2)^{1/2}}] \\
& - \frac{1}{2}[-A_2^2\ln\frac{1}{x_i^2+c^2+A_2^2} + A^2\ln\frac{1}{x_i^2+c^2+A^2} - A_1^2\ln\frac{1}{x_i^2+c^2+A_1^2} \\
& + A_3^2\ln\frac{1}{x_i^2+c^2+A_3^2}]\} \qquad \text{(B.13)}
\end{aligned}$$

Addition of Eqs. (B.11), (B.12) and (B.13) gives the result of integration of Eq. (B.10) with respect to x_i. After back substitution and rearranging it is found to be

$$
\begin{aligned}
F_{A_i-A_j} = \frac{c^2}{\pi b\ L_f}\ \{ & \frac{1}{c}[(L_f-sa)\tan^{-1}\frac{L_f-sa}{c} - sa\ \tan^{-1}\frac{sa}{c} \\
& + (s-1)a\ \tan^{-1}\frac{(s-1)a}{c} - (L_f-(s-1)a)\tan^{-1}\frac{L_f-(s-1)a}{c}] \\
& - \frac{(b^2+c^2)^{1/2}}{c^2}[(L_f-sa)\tan^{-1}\frac{L_f-sa}{(b^2+c^2)^{1/2}} - sa\ \tan^{-1}\frac{sa}{(b^2+c^2)^{1/2}} \\
& + (s-1)a\ \tan^{-1}\frac{(s-1)a}{(b^2+c^2)^{1/2}} - (L_f-(s-1)a)\tan^{-1}\frac{L_f-(s-1)a}{(b^2+c^2)^{1/2}}] \\
& - \frac{b^2}{c^2}[(c^2+(L_f-sa)^2)^{1/2}\tan^{-1}\frac{b}{(c^2+(L_f-sa)^2)^{1/2}} \\
& - (c^2+s^2a^2)^{1/2}\tan^{-1}\frac{b}{(c^2+s^2a^2)^{1/2}} \\
& + (c^2+(s-1)^2a^2)^{1/2}\tan^{-1}\frac{b}{(c^2+(s-1)^2a^2)^{1/2}} \\
& - (c^2+(L_f-(s-1)a)^2)^{1/2}\tan^{-1}\frac{b}{(c^2+(L_f-(s-1)a)^2)^{1/2}}] \\
& + \frac{1}{2}[\ln\frac{c^2+(L_f-sa)^2+b^2}{c^2+(L_f-sa)^2} - \ln\frac{c^2+s^2a^2+b^2}{c^2+s^2a^2} + \ln\frac{c^2+(s-1)^2a^2+b^2}{c^2+(s-1)^2a^2} \\
& - \ln\frac{c^2+(L_f-(s-1)a)^2+b^2}{c^2+(L_f-(s-1)a)^2}]\}
\end{aligned}
\tag{B.14}
$$

Which is the angle factor, Eq. (3.74).

For two equal planes $sa = L_f$ and $(s-1)a = 0$, Eq. (B.14) after rearranging becomes

$$F_{A_i-A_j} = \frac{2c^2}{\pi b L_f}\{\ln\left(\frac{(c^2+b^2)(c^2+L_f^2)}{c^2(c^2+L_f^2+b^2)}\right)^{1/2} - \frac{1}{c}[L_f \tan^{-1}\frac{L_f}{c} + b\tan^{-1}\frac{b}{c}]$$

$$+ \frac{1}{c^2}[b(c^2+L_f^2)^{1/2}\tan^{-1}\frac{b}{(c^2+L_f^2)^{1/2}}$$

$$+ L_f(b^2+c^2)^{1/2}\tan^{-1}\frac{b}{(c^2+L_f^2)^{1/2}}]\} \qquad \text{(B.15)}$$

Equation (B.15) is the same as the equation found in literature [33].

APPENDIX C : VARIABLES USED IN COMPUTER PROGRAMS

AB = Base area (ft**2)
ABR = Base area of radiation section (ft**2)
ADIAFT= Subroutine which makes energy balance in the furnace
AE = Excess air %
AFN = Theoretical air flow (kmole/hr)
AFR = Total air flow (kmole/hr)
ALEV = Total radiation heat transfer (kcal/hr)
ALFA = Void fraction
ALRB = Length of average radiant beam (m)
AT = Tube area (ft**2)
ATC = Tube area in convection section (ft**2)
ATCS = Tube area in convection section (m**2)
ATER = Total exchange area in radiation section(ft**2)
ATI = Air inlet temperature ('K)
ATR = Tube area in radiation section (ft**2)
ATRS = Tube area in radiation section (m**2)
ATT = Total tube of convection section area (ft**2)
ATTR = Total tube of radiation section area (ft**2)
AW = Wall area of convection section (ft**2)
AWR = Wall area of radiation section (ft**2)
BC = Length of the convection section (ft)
BINC = Conversion factor for iteration in temperature
BR = Length of the radiation section (ft)
CAPI = API gravity of charge
CBT = Charge boiling temp. at 1 atm. ('F)
CBTP = Charge boiling temp. at CPO ('K)
CF = Volumetric flow of charge (m**3/day)
CK = K factor of charge
CM = Mass flow rate of charge (kg/hr)
CMW = Molecular weight of charge
CMWPF = Molecular weight of petroleum fractions
COM = Carbon dioxide flow in flue gas (kmole/hr)
COMG = Carbon dioxide flow in flue gas from fuel gas (kmole/hr)
COMO = Carbon dioxide flow in flue gas from fuel oil (kmole/hr)
CON = Carbon dioxide mole fraction in flue gas

CPCG = Gas phase specific heat of charge (kcal/kg-'C)
CPCL = Liquid phase specific heat of charge (kcal/kg-'C)
CPGI = Integrated specific heat of flue gas (kcal/kmole-'K)
CPI = Inlet pressure of charge (atm)
CPIC = Charge inlet pres. in conv. sect. (atm)
CPIR = Charge inlet pres. in rad. sect. (atm)
CPIRT = Charge inlet pressure at the inlet of two phase region (atm)
CPO = Charge outlet pressure (atm)
CPOC = Charge outlet pres. in conv. sect. (atm)
CPOR = Charge outlet pres. in rad. sect. (atm)
CPRIC = Charge inlet pressure at the inlet of ceiling (atm)
CSG = Specific gravity of charge
CTA = Average charge temperature in the furnace (K)
CTB = Charge bulk temp. in conv. sect. ('K)
CTBR = Charge bulk temp. in rad. sect. ('K)
CTI = Inlet temperature of charge ('K)
CTIC = Charge inlet temp. in conv. sect. ('K)
CTIR = Charge inlet temp. in rad. sect. ('K)
CTIRT = Charge inlet temperature at the inlet of two phase region (K
CTO = Charge outlet temp. ('K)
CTOC = Charge outlet temp. in conv. sect. ('K)
CTOR = Charge outlet temp. in rad. sect. ('K)
CTRIC = Charge inlet temperature at the inlet of ceiling (K)
DATA = Subroutine which contains input
DEL = Constants of accuracy
DHG = Gas phase hydroulic radius (ft)
DHL = Liquid phase hydroulic radius (ft)
DI = Inside tube diameter (ft)
DIC = Inside tube diameter in convection section (ft)
DICS = Inside tube diameter in convection section (m)
DIR = Inside tube diameter in radiation section (ft)
DIRS = Inside tube diameter in radiation section (m)
DNMA = Nitrogen flow in fuel gas from air (kmole/hr)
DNMG = Nitrogen flow in flue gas from fuel gas (kmole/hr)
DNN = Nitrogen mole fraction in flue gas
DO = Outside tube diameter (ft)
DOC = Outside tube diameter in convection section (ft)
DOMA = Oxygen flow in fuel gas from air (kmole/hr)
DOR = Outside tube diameter in radiation section (ft)
DRO = Difference in densities of liquid & gas phases of charge
EF = Emissivity of flame
EPS = Constant of accuracy
ERROR = Error of the program
FAY = Radiation exchange factor
FCC = Convective heat transfer correction factor in Chen correlatic

FFC = Friction factor for charge
FGF = Fuel gas flow rate (m**3/hr)
FGFLOR= Subroutine which makes mass balance in the furnace
FGM = Fuel gas molar flow (m**3/hr)
FGMC = Fuel gas molar composition
FGMF1 = Molar flow of hydrogen sulfide in fuel gas (kmole/hr)
FGMF10= Molar flow of HC having 4(iso) carbon in fuel gas (kmole/hr)
FGMF11= Molar flow of HC having 4(normal) carbon in fuel gas(kmole/hr)
FGMF2 = Molar flow of hydrogen in fuel gas(kmole/hr)
FGMF3 = Molar flow of nitrogen in fuel gas(kmole/hr)
FGMF4 = Molar flow of oxygen in fuel gas(kmole/hr)
FGMF5 = Molar flow of carbon dioxide in fuel gas(kmole/hr)
FGMF6 = Molar flow of carbon monoxide in fuel gas(kmole/hr)
FGMF7 = Molar flow of methane in fuel gas(kmole/hr)
FGMF8 = Molar flow of HC having 2 carbon in fuel gas(kmole/hr)
FGMF9 = Molar flow of HC having 3 carbon in fuel gas(kmole/hr)
FGPI = Fuel gas inlet pressure (atm)
FGSG = Fuel gas specific gravity
FGTI = Fuel gas inlet temperature ('K)
FL = Flame length (ft)
FLAME = Radiation heat transfer at each stage (kcal/hr)
FOAPI = Fuel oil API gravity
FOC = Fuel oil carbon fraction
FOCM = Molar flow of carbon in fuel oil (kmole/hr)
FOF = Flow rate of fuel oil (lt/min)
FOH = Fuel oil hydrogen fraction
FOHM = Molar flow of hydrogen in fuel oil (kmole/hr)
FOK = Fuel oil K value
FORO = Fuel oil density (kg/lt)
FOS = Sulfur fraction of fuel oil
FOSG = Fuel oil specific gravity
FOSM = Sulfur molar flow in fuel oil (kmole/hr)
FOTI =Fuel oil inlet temperature ('K)
FOV = Fuel oil viscosity at 122'F (centistoke)
FOW = Fuel oil mass flow (kg/hr)
GC = Mass flow rate of charge (lb/hr-ft**2)
GG = Flue gas mass flow rate in conv. sec. (lb/hr-ft**2)
GGR = Flue gas mass flow rate in rad. sec. (lb/hr-ft**2)
HB = Heat transfer cofficient from walls by radiation(Btu/hr-m2-'K)
HC = Heat transfer cofficient from gas by convection(Btu/hr-m2-'K)
HCS = Heigth of the convection section (ft)
HG = Enthalpy of flue gas (kcal/hr)
HI = Heat trans. coeff. in the inside of tubes (kcal/K-m2-hr)
HIG = Inside heat trans. coeff. of charge (gas phase) (kcal/K-m2-hr)
HIL = Inside heat trans. coeff. of charge (liq.phase) (kcal/K-m2-hr)

HITP = Two phase inside heat transfer coeff. of charge (kcal/hr-K-
HMAC = Macroscopic heat transfer coeff. of charge (kcal/K-m2-hr)
HMIC = Microscopic heat transfer coeff. of charge (kcal/K-m2-hr)
HNUC = Nucleate boiling heat trans. coeff. of charge (kcal/K-m2-hr)
HO = Heat transfer coeff. on the outside of tubes (kcal/'K-m**2-
HOM = Water vapor flow in flue gas (kmole/hr)
HOMA = Water vapor flow in fuel gas from air (kmole/hr)
HOMG = Water vapor flow in flue gas from fuel gas (kmole/hr)
HOMO = Water vapor flow in flue gas from fuel oil (kmole/hr)
HOMS = Water vapor flow in flue gas from steam (kmole/hr)
HON = Water vapor mole fraction in flue gas
HR = Heat transfer coefficient from gas by radiation(kcal/hr-m2-
HRS = Heigth of the radiation section (ft)
HSI = Enthalpy of steam at inlet condition (kcal/hr)
HSTEAM= Enthalpy of steam (kcal/kg)
HVC = Latent heat of vaporization of charge (kcal/kg)
HVPF = Latent heat of vaporization of petroleum fractions (kcal/kg)
K = UOP-K factor
KONVEK= Subroutine which finds temp. distribution in conv. sec.
M = Number of tubes in each stage
N = Number of stages
NC = Number of stages in convection section
NR = Number of stages in radiation section
OM = Oxygen flow in flue gas (kmole/hr)
ON = Oxygen mole fraction in flue gas
ONF = Oxygen needed for total fuel (kmole/hr)
ONFG = Oxygen needed for fuel gas (kmole/hr)
ONFO = Oxygen needed for fuel oil (kmole/hr)
PO = Referance pressure (atm)
PFKVAL= Characterization factor of petroleum fractions
PP = Partial press.of carbon dioxide + water vap.in flue gas (atm
PR = Prandtl number
PRG = Gas phase Prandtl number
PRINTI= Subroutine which writes input
PRINTO= Subroutine which writes output
PRL = Liquid phase Prandtl number
PS = Saturation pressure(atm)
PT = Pressure of radiation section (atm)
QC = Heat of combustion of fuel (kcal/hr)
QCFG = Heat of combustion of fuel gas (kcal/hr)
QCFO = Heat of combustion of fuel oil (kcal/hr)
QCHARG= Heat absorbed by charge in the furnace (kcal/hr)
QG = Heat given by flue gas in each stage of conv. sec. (kcal/hr)
QGAS = Heat given by gas in the furnace (kcal/hr)
QGR = Heat given by flue gas in each stage of rad. sec. (kcal/hr)

QS = Sensible heat of inputs (kcal/hr)
QSA = Sensible heat of air (kcal/hr)
QSFG = Sensible heat of fuel gas (kcal/hr)
QSFO = Sensible heat of fuel oil (kcal/hr)
QSS = Sensible heat of steam (kcal/hr)
QT = Total heat of input (kcal/hr)
R = Universal gas constant (atm-lt/kmole-'K)
RADYAS= Subroutine which finds temp. distribution in rad. sec.
RE = Reynolds number
REG. = Gas phase reynolds number
REL = Liquid phase reynolds number
RETP = Two phase Reynolds number
RO1 = Liquid phase density of charge at 60'F (lb/ft**3)
ROA = Density of air (kg/m**3)
ROCG = Gas phase density of charge (kmole/m**3)
ROCL = Liquid phase density of charge (lb/ft**3)
ROG = Gas phase density of charge (kg/m**3)
ROW = Density of water (lb/ft**3)
RSINPH= Subroutine which finds temp.distr.in rad.sec. for single phase
RTWOPH= Subroutine which finds temp.distr.in rad. sec. for two phase
RW = Fraction of radiation reflected from walls
S = Nucleate boiling suppression factor in Chen correlation
SFCFS = Radiation angle factor (flame to ceiling strip)
SFFS = Radiation angle factor (flame to strip)
SG = Specific gravity
SIGMA = Stephan-Boltzman constant (kcal/m**2-hr-'K**4)
SL = Staggering distance (ft)
SOM = Sulfur dioxide flow in flue gas (kmole/hr)
SOMG = Sulfur dioxide flow in flue gas from fuel gas (kmole/hr)
SOMO = Sulfur dioxide flow in flue gas from fuel oil (kmole/hr)
SON = Sulfur dioxide mole fraction in flue gas
SPI = Atomizing steam inlet pressure (atm)
ST = Staggering distance of tubes in convection (m)
STC = Surface tension of charge (N/m)
STI = Atomizing steam inlet temperature ('K)
STW = Surface tension of water (N/m)
SW = Atomizing steam mass flow (kg/hr)
T = Temperature ('K)
TO = Reference temperature ('K)
TOC = Reference temperature ('C)
TOF = Reference temperature ('F)
TAG = Average gas temperature in the furnace (K)
TC = Temperature ('C)
TCG = Gas phase thermal conductivity charge (Btu/hr-ft-'K)
TCL = Liquid phase thermal conductivity charge (Btu/hr-ft-'K)

TF = Adiabatic flame temp. ('K)
TFC = Critical temperature of charge ('F)
TG = Flue gas temperature ('K)
TGA = Average gas temperature in convection section('K)
TGAR = Average gas temperature in radiation section('K)
TGCO = Flue gas temperature at the inlet of conv. sec. (K)
TGNW = Calculated gas temperature in convection section('K)
TGO = Gas temperature at the outlet to the stack ('K)
TGR = Gas temperature in radiation section('K)
TGR1 = Gas temperature at the bottom of radiation section('K)
TGRC = Flue gas temperature at the inlet of ceiling region (K)
TGRN = Calculated gas temperature in radiation section('K)
TGRT = Flue gas temperature at the inlet of two phase region (K)
TLC = Tube length in convection section (m)
TLR = Tube length in radiation section (m)
TPHTC = Subroutine which finds two phase heat trans. coeff.
TR = Reduced temperature
TR1C = Reduced temperature of charge at 60'F
TRC = Reduced temperature of charge
TS = Saturation temperature (K)
TSA = Average surface temp. ('K)
TSAC = Average surface temperature of tube in convection section (K)
TSC = Surface temp. in conv. sect. ('K)
TSR = Surface temperature of tube in radiation section (K)
TSRC = Tube surface temperature at the inlet of ceiling region (K)
TSRT = Tube surface temperature at the inlet of two phase region (K)
V1 = Viscosity (cs) of charge at temp. TC1 (K)
V2 = Viscosity (cs) of charge at temp. TC2 (K)
VC = Viscosity of charge (lb/hr-ft)
VCA = Viscosity of air (cp)
VCG = Gas phase viscosity of charge (cp)
VCW = Viscosity of water (lb/hr-ft)
VELG = Gas phase superficial velocity (m/s)
VELL = Liquid phase superficial velocity (m/s)
W1 = Expansion coefficient of charge at 60'F
WC = Width of the convection section (ft)
WG = Molar flow of flue gas (kmole/hr)
WGM = Molecular weight of flue gas (kg/kmole)
WR = Width of the radiation section (ft)
X = Fraction of charge vaporized at each stage
XC = Fraction of charge vaporized at wall tubes
XJC = Vapor mass fraction of charge
XSI = Constant of accuracy
XTT = Martinelli parameter
Z = Temp. increment at each stage

APPENDIX D : LISTING OF THE COMPUTER PROGRAM

```
C------------------------------------------------------------------
C      M   M    A     I  N    N
C      MM MM   A A    I  N N  N
C      M M M  AAAAA   I  N  N N
C      M   M  A   A   I  N   NN
C------------------------------------------------------------------
C
C
C
C     THIS PROGRAM FINDS THE TEMPERATURE DISTRIBUTION IN BORN TYPE
C     MULTIFUEL FURNACE PLUS THE TEMPERATURE & PRESSURE  OF CHARGE
C     AT THE INLET OF EACH TUBE. THE FURNACE IS ANALYZED IN MAINLY
C     TWO SECTIONS,EACH IS DIVIDED INTO NUMBER OF STAGES  EQUALING
C     TO NUMBER OF TUBES ALONG THE HEIGHT AND SYMMETRY IS ASSUMED.
C     THE CHARGE,WHICH IS THE BOTTOM PRODUCT OF ATMOSPHERIC DISTIL-
C     LATION TOWER, ENTERS THE  CONVECTION  SECTION IN THE  LIQUID
C     PHASE AND LEAVES THE CEILING OF THE RADIATION SECTION IN TWO
C     PHASE,HALF LIQUID  HALF VAPOR. IN THE CONVECTION SECTION HOT
C     FLUE GAS FLOWS ACROSS THE TUBE BANKS.IN THE RADIATION SECTION
C     TUBES ARE ON THE  SIDE WALLS AND  LAST ONES ON THE  CEILING.
C     THEREFORE THE FLOW OF FLUE GAS IS  PERPENDICULAR AND TANGEN_
C     TIAL.ALL THE TUBES OF RADIATION SECTION SEE THE  FLAME. THIS
C     SECTION IS ANALYZED IN THREE SUBSECTIONS:
C
C     1_LIQUID PHASE : THE CHARGE FLOW IS INSIDE THE TUBES ON THE
C                      WALL.
C     2_TWO PHASE    : THE CHARGE FLOW IS INSIDE THE TUBES ON THE
C                      WALL.
C     3_TWO PHASE    : THE CHARGE FLOW IS INSIDE THE TUBES ON THE
C                      CEILING.
C
C
C  *****************MAIN********************
C
C
      COMMON /A01/ R01,W1,TFC,CBT
      COMMON /B01/ WG,WGM,AFR
      COMMON /B02/ CON,HON,SON,ON,DNN
      COMMON /A02/ CM,GC
      COMMON /CI/  TGO,CTI,DIC,TLC,CPI,ST,ATC,DOC,WC,BC,HCS,NC,M
      COMMON /C05/ CTIC(7,2),CTOC(7,2),CPIC(7,2),CPOC(7,2),
     &             TSC(7,2),TSAC(7),TGC(7)
      COMMON /BI/  FOF,FOS,FOAPI,FGF,FGTI,FGPI,FGMC(11),AE,AH,FGSG
      COMMON /EI/  FOV,FOTI,STI,SPI,ATI,TO,PO
      COMMON /E0/  TF
      COMMON /GI/  DIR,ATR,ALRB,TLR,DOR
      COMMON /G02/ CTIR(25),CTOR(25).CPIR(25),CPOR(25),TSR(25),TGR(25)
      COMMON /A03/ CSG
```

```
      COMMON /AI1/ PT
      COMMON /AI2/ HRS,BR,WR,FL,NR
      COMMON /AI3/ DI,CK,CAPI,CF
      COMMON /E01/ SW
      COMMON /C03/ SL,GG,AW,ATE
      COMMON /G08/ XJC(25),HVC
      COMMON /H/   V1,V2,TC1,TC2
      COMMON /E02/ QT
      COMMON /ERR/ QGAS,QCHARGE,ERROR,ERROR1
C
      CALL DATA
C
      CALL PRINTI
C
      CSG  = 141.5 / ( 131.5 + CAPI )
      CM   =( CSG * CF * 1000./ 24.)/2.
      GC   = CM * 2.2046226 * 4./ ( 4 * ATAN(1.)* DI * DI )
      CBT  = ( CK * CSG ) ** 3.-460.
      AC   = ( CBT + 100. ) * CSG
      TFC  = 180. + 1.75 * AC - 0.0008 * AC * AC
      TR1C = 60. / TFC
      W1   = 0.1745 - 0.0838 * TR1C
      R01  = CSG * 62.37364867
C
      CALL FGFLOR
C
      CALL KONVEK
C
      CALL RADYAS
C
      CTA=(CTOR(25)+CTI)/2.
      TAG=(TGR(1)+725.)/2.
      QCHARGE=CM*2.*((CTOR(25)-CTI)*CPCL(CTA)+XJC(25)*HVC)
      QGAS   =WG*(TGR(1)-725.)*CPGIT(TAG)
      ERROR=((QCHARGE-QGAS)/QCHARGE)*100.
      CALL ADIAFT
      ERROR1=((QT-QGAS)/QT)*100.
C
      CALL PRINTO
C
      STOP
      END
C
C
C
C-------------------------------------------------------------------------
C     DDD       A     TTTTT    A
C     D  D     A A      T     A A
C     D  D    AAAAA     T    AAAAA
C     DDD    A     A    T   A     A
C-------------------------------------------------------------------------
C
C
C
```

```
      SUBROUTINE DATA
C
C
C     THIS SUBROUTINE CONTAINS THE NECCESSARY DATA TO RUN THE FURNACE
C     PROGRAM
C
      DIMENSION FGMC(11)
      COMMON /AI1/ PT
      COMMON /AI2/ HRS,BR,WR,FL,NR
      COMMON /AI3/ DI,CK,CAPI,CF
      COMMON /BI/  FOF,FOS,FOAPI,FGF,FGTI,FGPI,FGMC(11),AE,AH,FGSG
      COMMON /CI/  TGO,CTI,DIC,TLC,CPI,ST,ATC,DOC,WC,BC,HCS,NC,M
      COMMON /EI/  FOV,FOTI,STI,SPI,ATI,TO,PO
      COMMON /GI/  DIR,ATR,ALRB,TLR,DOR
      COMMON /H/   V1,V2,TC1,TC2
C
C     DATA OF FUEL OIL: FOF  = Flow rate (lt/min)
C                       FOS  = Sulfur mass fraction
C                       FOAPI= API gravity
C                       FOV  = Viscosity at 122 F (cs).
C                       FOTI = Inlet temperature (K)
C
      DATA   FOF,FOS,FOAPI,FOV,FOTI / 32.3,0.0394,11.4,2320.,407. /
C
C     DATA OF FUEL GAS: FGF  = Flow rate (cu.m/hr)
C                       FGTI = Inlet temperature (K)
C                       FGPI = Inlet pressure (atm)
C                       FGSG = Specific gravity
C                       FGMC(1) = Volumetric fraction of H2S
C                       FGMC(2) = Volumetric fraction of H2
C                       FGMC(3) = Volumetric fraction of N2
C                       FGMC(4) = Volumetric fraction of O2
C                       FGMC(5) = Volumetric fraction of CO2
C                       FGMC(6) = Volumetric fraction of CO
C                       FGMC(7) = Volumetric fraction of C1
C                       FGMC(8) = Volumetric fraction of C2
C                       FGMC(9) = Volumetric fraction of C3
C                       FGMC(10)= Volumetric fraction of IC4
C                       FGMC(11)= Volumetric fraction of NC4
C
      DATA   FGF,FGTI,FGPI,FGSG / 316.9,293.,3.552 ,.547/
      DATA   ( FGMC(I),I=1,11 ) /0.009,0.46,
     &       0.064,0.004,0.003,0.012,0.193,0.12,0.102,0.0165,0.0165 /
C
C     DATA OF STEAM:    STI  = Inlet temperature (K)
C                       SPI  = Inlet pressure (atm)
C
      DATA   STI,SPI / 588.,37.425 /
C
C     DATA OF AIR:      AE   = Percentage of excess air
C                       ATI  = Inlet temperature (K)
C
      DATA   AE,ATI / 23.,293. /
C
```

```
C     DATA OF CHARGE:    CK   = Characterization factor
C                        CTI  = Inlet temperature (K)
C                        CPI  = Inlet pressure (atm)
C                        CAPI = API gravity
C                        CF   = Flow rate (cu.m/day)
C                        DI   = Tube inside diameter at charge inlet (ft)
C                        V1   = Viscosity (cs) at temperature TC1 (K)
C                        V2   = Viscosity (cs) at temperature TC2 (K)
C
      DATA   CK,CTI,CPI,CAPI,CF,DI / 11.68,583.,3.8713,20.4,7000.,
     &                             0.5521 /
      DATA   V1,V2,TC1,TC2 / 7.3,63.,371.9,323. /
C
C     DATA OF FLUE GAS: TGO  = Flue gas temperature at stack inlet (K)
C                       PT   = Total gas side pressure of the furnace (a
C                       FL   = Flame length (ft)
C                       ALRB = Average length of radiant beam (ft)
C
      DATA   TGO,PT,FL,ALRB / 725.,1.,6.5617,14.7999/
C
C     DATA OF CONVECTION SECTION:
C                        DIC  = Tube inside diameter (ft)
C                        TLC  = Tube length (m)
C                        ST   = Staggering distance (ft)
C                        ATC  = Total tube area (sq.ft)
C                        NC   = Number of tube rows
C                        M    = Number of tubes per row
C                        DOC  = Tube outside diameter (ft)
C                        WC   = Width (ft)
C                        BC   = Length (ft)
C                        HCS  = Heigth (ft)
C
      DATA   DIC,TLC,ST,ATC,NC,M,DOC,WC,BC,HCS / 0.5306,19.964,
     &       1.,268.9583,6,4,0.5521,5.0033,72.8018,10.561 /
C
C     DATA OF RADIATION SECTION:
C                        HRS  = Heigth (ft)
C                        BR   = Length (ft)
C                        WR   = Width (ft)
C                        NR   = Number of tube rows
C                        DIR  = Tube inside diameter (ft)
C                        ATR  = Total tube area (sq.ft)
C                        DOR  = Tube outside diameter (ft)
C                        TLR  = Tube length (m)
C
      DATA   HRS,BR,WR,NR,DIR,ATR,DOR,TLR / 27.5066,
     &      70.8018,11.3845,23.,0.6973,126.8519,0.7188,19.964 /
C
C     DATA OF REFERENCE CONDITION:
C                        TO   = Inlet temperature (K)
C                        PO   = Inlet pressure (atm)
C
      DATA  TO,PO / 298.,1. /
C
      RETURN
      END
```

```
C
C
C
C---------------------------------------------------------------------
C     PPPPP  RRRRR  I  N    N  TTTTT  I
C     P   P  R   R  I  N N  N    T    I
C     PPPPP  RRRR   I  N  N N    T    I
C     P      R   R  I  N    N    T    I
C---------------------------------------------------------------------
C
C
C
      SUBROUTINE PRINTI
C
C THIS SUBROUTINE PRINTS THE INPUT DATA OF FURNACE PROGRAM
C
      DIMENSION FGC(11)
C
      COMMON /AI1/ PT
      COMMON /AI2/ HRS,BR,WR,FL,NR
      COMMON /AI3/ DI,CK,CAPI,CF
      COMMON /BI/  FOF,FOS,FOAPI,FGF,FGTI,FGPI,FGMC(11),AE,AH
      COMMON /CI/  TGO,CTI,DIC,TLC,CPI,ST,ATC,DOC,WC,BC,HCS,NC,M
      COMMON /EI/  FOV,FOTI,STI,SPI,ATI,TO,PO
      COMMON /GI/  DIR,ATR,ALRB,TLR,DOR
      COMMON /H/   V1,V2,TC1,TC2
C
      WRITE(3,1) TO,PO
    1 FORMAT(1H,/////,10X,'DATA OF THE FURNACE PROGRAM',/,
     &10X,30('_'),///,10X,'REFERENCE CONDITIONS:',3X,'TEMPERATURE=',
     &F5.1,'K',/,34X,'PRESSURE=',F5.1,'ATM')
C
      WRITE(3,2)AE,AH,ATI
    2 FORMAT(//,10X,'DATA OF AIR:',12X,'EXCESS AIR=',F7.3,'%',
     &/,34X,'HUMIDITY=',F7.3,'%',/,34X,'INLET TEMP.=',F5.1,'K')
C
      WRITE(3,3)FOF,FOS,FOAPI,FOV,FOTI
    3 FORMAT(//,10X,'DATA OF FUEL OIL:',5X,'FLOW RATE='
     &,F10.5,'LT/MIN',/,34X,
     &'SULFUR MASS FRACTION=',F6.5,/,34X,'API GRAVITY=',F5.2,/,34X,
     &'VISCOSITY AT 122F=',F10.5,'CS',/,34X,'INLET TEMP.=',F6.2,'K')
C
      WRITE(3,4)STI,SPI
    4 FORMAT(//,10X,'DATA OF STEAM:',10X,'INLET TEMP.=',F6.2,'K',/,
     &34X,'INLET PRESS.=',F6.2,'ATM')
C
      WRITE(3,5)FGF,FGTI,FGPI,(FGMC(I),I=1,11)
    5 FORMAT(//,10X,'DATA OF FUEL GAS:',7X,'FLOW RATE=',F10.5,'M**3
     &/HR',/,34X,'INLET TEMP.=',F6.2,'K',/,34X,'INLET PRESS.=',F6.2
     &,'ATM',/,34X,'MOLE FRACTIONS OF H2S=',F6.5,/,53X,'H2=',F6.5,/
     &,53X,'N2=',F6.5,/,53X,'O2=',F6.5,/,53X,'CO2=',F6.5,/
     &,53X,'CO=',F6.5,/,53X,'C1=',F6.5,/,53X,'C2=',F6.5,/,53X,'C3='
     &,F6.5,/,53X,'IC4=',F6.5,/,53X,'NC4=',F6.5)
C
```

```
      WRITE(3,6)TGO,PT,FL,ALRB
    6 FORMAT(//,10X,'DATA OF FLUE GAS:',7X,'TEMP. AT THE OUTLET TO
     &STACK=',F6.2,'K',/,34X,'TOTAL PRESSURE=',F6.2,'ATM',/,34X,
     &'FLAME LENGTH=',F7.3,'FT.',/,34X,'AVERAGE LENGTH OF RADIANT
     &BEAM=',F7.3,'FT.')
C
      WRITE(3,7)CK,CTI,CPI,CAPI,CF,DI,V1,TL1,V2,TC2
    7 FORMAT(//,10X,'DATA OF CHARGE:',9X,'UOP-K=',F5.2,/,34X,'INLET
     & TEMP.=',F6.2,'K',/,34X,'INLET PRESS.=',F6.2,'ATM',/,34X,'API
     & GRAVITY=',F5.2,/,34X,'FLOW RATE=',F10.3,'M**3/D',/,34X,'INLET
     & PARAMETER=',F6.4,'FT.',/,34X,'VISCOSITY=',F10.5,'CST',4X,'AT
     & TEMPERATURE=',F6.2,'K',/,34X,'VISCOSITY=',F10.5,'CST',4X,'AT
     & TEMPERATURE=',F6.2,'K')
C
      WRITE(3,8)TLC,DIC,DOC,ST,NC,M,ATC,WC,BC,HCS
    8 FORMAT(//,10X,'DATA OF CONVECTION SECTION:',3X,'TUBE LENGTH='
     &,F6.3,'M',/,36X,'INSIDE DIAMETER=',F6.3,'FT',/,36X,'OUTSIDE
     & DIAMETER=',F6.3,'FT',/,36X,'STAGGERING DISTANCE=',F6.3,'FT',
     &/,36X,'# OF ROWS=',I2,/,36X,'# OF TUBES / ROW=',I2,/,36X,'
     &TOTAL AREA=',F10.3,'FT**2',/,36X,'DIMENSIONS OF THE SECTION=',
     &1X,'WIDTH=',F10.3,'FT',/,57X,'LENGTH=',F6.3,'FT',/,57X,'HIGHT='
     &,F6.3,'FT.')
C
      WRITE(3,9)WR,BR,HRS,NR,DIR,DOR,TLR,ATR
    9 FORMAT(//,10X,'DATA OF RADIATION SECTION:',4X,'DIMENSIONS OF
     &THE SECTION=',5X,'WIDTH=',F6.3,'FT.',/,57X,'LENGTH=',F6.3,'FT'
     &,/,57X,'HEIGHT=',F6.3,'FT',/,30X,'TUBE NUMBER=',I2,/,36X,
     &'INSIDE DIAMETER=',F6.3,'FT.',/,36X,'OUTSIDE DIAMETER=',F6.3,
     &'FT.',/,36X,'LENGTH=',F6.3,'M',/,36X,'TOTAL AREA=',F10.3,'FT
     &**2')
C
      RETURN
      END
C
C
C
C-------------------------------------------------------------------
C     FFFFF  GGGGG  FFFFF  L      OOOOO  RRRRR
C     F      G      F      L      O   O  R   R
C     FFF    GGGGG  FFF    L      O   O  RRRRR
C     F      GGGGG  F      LLLLL  OOOOO  R  RR
C-------------------------------------------------------------------
C
C
C
      SUBROUTINE FGFLOR
C
C CALCULATES THE FLUE GAS FLOW RATE & COMPOSITION & MOLECULAR WEIGHT
C ON THE BASIS OF KMOLE/HR
C
C INPUT:FOF,FOS,FOAPI,FGF,FGTI,FGPI,FGMC(11),AE,AH
C OUTPUT:WG,AFR,CON,SON,HON,DNN,ON,WGM
C
      COMMON /BI/  FOF,FOS,FOAPI,FGF,FGTI,FGPI,FGMC(11),AE,AH,FGSG
```

```
      COMMON /B01/ WG,WGM,AFR
      COMMON /B02/ CON,HON,SON,ON,DNN
      COMMON /E01/ SW
C
      DIMENSION FGMF(11)
C
C   CALCULATIONS ON FUEL OIL
C     FUEL OIL COMPOSITION (MASS FRACTION)
C
      FOSG = 141.5 / (131.5 + FOAPI)
      FORO = 1. * FOSG
      FOW  = FOF * 60. * FORO
      FOH  = (26. - 15. * FOSG) / 100.
      FOC  = 1. - FOH - FOS
C
C     MOLAR FLOW OF EACH COMPONENT (KMOLE/HR)
C
      FOSM = FOW * FOS / 32.
      FOHM = FOW * FOH / 2.
      FOCM = FOW * FOC / 12.
C
C     OXYGEN NEEDED FOR COMBUSTION (KMOLE/HR)
C
      ONFO = FOCM + FOSM + 0.5 * FOHM
C
C     MOLAR FLOW OF PRODUCTS (KMOLE/HR)
C
      COMO = FOCM
      SOMO = FOSM
      HOMO = FOHM
C
C   MOLAR FLOW OF STEAM (KMOLE/HR)
C
      SW   = FOW* 0.3056
      HOMS = SW / 18.
C
C   CALCULATIONS ON FUEL GAS
C     MOLAR FLOW OF FUEL GAS (KMOLE/HR)
C
      FGM  = FGPI * FGF / (FGTI * 0.0820567)
      FGW  = FGSG * FGF * .0808 * 16.018
C
C     MOLAR FLOW OF COMPONENTS (KMOLE/HR)
C
      DO 1 I=1,11
      FGMF(I) = FGM * FGMC(I)
    1 CONTINUE
C
C     OXYGEN NEEDED FOR COMBUSTION (KMOLE/HR)
C
      ONEG = 0.5 * (FGMF(2) + FGMF(6) + 3. * FGMF(1) + 4. * FGMF(7) +
     &       6.5 * FGMF(8) + 9.5 * FGMF(9) + 12.5 * (FGMF(10)+FGMF(11))
     &       - FGMF(4)
C
```

```
C     MOLAR FLOW OF PRODUCTS (KMOLE/HR)
C
      DNMG = FGMF(3)
      COMG = FGMF(5) + FGMF(6) + FGMF(7) + 2. * FGMF(8) + 3. * FGMF(9)
     &       + 4. * (FGMF(10) + FGMF(11))
      SOMG = FGMF(1)
      HOMG = FGMF(2) + FGMF(1) + 2. * FGMF(7) + 2.5 * FGMF(8) + 3.5 *
     &       FGMF(9) + 4.5 * (FGMF(10) + FGMF(11))
C
C   TOTAL OXYGEN NEEDED FOR COMBUSTION OF FUEL (KMOLE/HR)
C
      ONF   = ONFO + ONFG
C
C   CALCULATIONS ON AIR (KMOLE/HR)
C
C     MOLAR FLOW RATE
C
      AFN   = ONF * 100. / 21.
      AFR   = AFN * (100 + AE) / 100.
      AW    = AFR * 28.84
C
C     MOLAR FLOW RATE OF AIR PRODUCTS (KMOLE/HR)
C
      DNMA = AFR *0.79
      DOMA = AFR * 0.21 - ONF
C
C  CALCULATIONS ON FLUE GAS
C
C     MOLAR FLOW RATE OF COMPONENTS (KMOLE/HR)
C
      COM   = COMO + COMG
      SOM   = SOMO + SOMG
      HOM   = HOMO + HOMG + HOMS
      DNM   = DNMG + DNMA
      OM    = DOMA
C
C     TOTAL MOLAR FLOW RATE OF FLUE GAS (KMOLE/HR)
C
      WG    = COM + SOM + HOM +DNM + OM
C
C     MOLE FRACTION OF COMPONENTS
C
      CON   = COM / WG
      SON   = SOM / WG
      HON   = HOM / WG
      DNN   = DNM / WG
      ON    = OM  / WG
C
C     MOLECULAR WEIGHT OF FLUE GAS (KMOLE/HR)
C
      WGM   = 44.* CON + 18.* HON + 64.* SON + 28.* DNN + 32.* ON
      WGW   = WGM *WG
      MASSIN =FOW+FGW+SW+AW
      ERROR = MASSIN-WGW
      RETURN
      END
```

```
C
C
C
C-----------------------------------------------------------------------
C     CCCCC   OOOOO   N     N  V       V  EEEEE   CCCCC
C     C       O   O   N N   N   V     V   E       C
C     C       O   O   N   N N    V V      EEE     C
C     CCCCC   OOOOO   N     N     V       EEEEE   CCCCC
C-----------------------------------------------------------------------
C
C
C
      SUBROUTINE KONVEK
C
C  FINDS TEMPERATURE DISTRIBUTION IN CONVECTION SECTION
C
C     INPUT:TGO,CTI,DIC,LC,CPI,ST,ATC,NC,M,DOC,EPSC,DELC,WC,BC,HC,CM,GC
C           WG,WGM
C     OUTPUT:CTIC(NC,M),CTOC(NC,M),CPIC(NC,M),CPOC(NC,M),TSC(NC,M)
C            TSAC(NC),TGC(NC),TGC(NC-1)
C
C
      COMMON /A01/ RO1,W1,TFC,CBT
      COMMON /B01/ WG,WGM,AFR
      COMMON /B02/ CON,HON,SON,ON,DNN
      COMMON /A02/ CM,GC
      COMMON /CI/  TGO,CTI,DIC,TLC,CPI,ST,ATC,DOC,WC,BC,HCS,NC,M
      COMMON /C05/ CTIC(7,2),CTOC(7,2),CPIC(7,2),CPOC(7,2),TSC(7,2),
     &           TSAC(7),TGC(7)
      COMMON /C02/ TGCO,CPRIC,CTRIC
      COMMON /A03/ CSG
      COMMON /AI3/ DI,CK,CAPI,CF
      COMMON /C03/ SL,GG,AW,ATE
C
      DIMENSION Z(15),TGNW(15),TS(7,2)
      DELC =5.
      EPSC =1.
C
C     CALCULATION OF VARIABLES USED AS CONSTANTS
C
      DICS        = DIC * 0.3048
      ATCS        = ATC * 0.0929
      SL          = (SQRT(3.) / 2.) * ST
      AW          = 2. * HCS * (BC + WC)
      ATT         = ATC * NC * M
      ATE         = ATT + AW
      AB          = BC * WC
      ABF         = AB-4.*DOC*BC
      GG          = ST * WG * WGM * 2.2046226 / ( (ST - DOC) * ABF)
      Z(1)        = 18.5
      TGC(1)      = TGO
      CTIC(2,1)   = CTI
      CPIC(2,1)   = CPI
C
```

```
C     CALCULATION OF TEMPERATURE & PRESSURE FOR EACH STAGE
C
      DO 2 J = 2, NC+1
           Z(J) = Z(J-1) + J
           TGC(J) = TGC(J-1) + Z(J)
    3      TGA = ( TGC(J) + TGC(J-1) ) / 2.
           QG  = WG * CPGI(TGC(J-1),TGC(J))
           TAS= 0.
           DO 1 I = 1, M/2
                CTIF = (CTIC(J,I) - 273.) * 1.8 + 32.
                CTOC(J,I) = CTIC(J,I) + QG /(M*CM*CPCL(CTIC(J,I)))
                CTB = ( CTIC(J,I) + CTOC(J,I) ) / 2.
                VC = VCC(CTB)
                TSC(J,I) = CTB + QG / (4 * 4 * ATAN(1.) * DICS * TLC *
     &                                HI(VC,CTB,DIC))
                TAS = TSC(J,I) + TAS
          CPOC(J,I)= CPIC(J,I)-(2.*(TLC+25*DICS) * (GC*GC) * 0.015
     &                      / (DICS * ROCL( CTB ))) * 1.1332335E-12
                CTIC(J,I+1) = CTOC(J,I)
                CPIC(J,I+1) = CPOC(J,I)
    1      CONTINUE
           TSAC(J) = TAS / (M * 0.5)
       TGNW(J) = 2. * TSAC(J) - TGC(J-1) +2.* QG/( ATCS * M *
     &              HO( TGA,TSAC(J),GG,DOC,AW,ATE ) )
           IF ( ABS ( TGNW(J) - TGC(J) ) .LE. EPSC ) GO TO 4
           BINC=.1
           TGC(J)=TGC(J)-BINC*( TGNW(J) - TGC(J) )
           GO TO 3
    4      CTIC(J+1,1) = CTOC(J,M/2)
           CPIC(J+1,1) = CPOC(J,M/2)
    2 CONTINUE
      TGCO  = TGC(NC+1)
      CTRIC = CTOC(NC+1,M/2)
      CPRIC = CPOC(NC+1,M/2)
      RETURN
      END
C
C
C
C---------------------------------------------------------------
C      RRRRR    A    DDDDD  Y   Y    A    SSSSS
C      R   R   A A   D   D  Y   Y   A A   S
C      RRRRR  AAAAA  D   D  YYYYY  AAAAA  SSSSS
C      R  RR  A   A  D   D    Y    A   A  SSSSS
C---------------------------------------------------------------
C
C
C
      SUBROUTINE RADYAS
C
C
C FINDS THE TEMPERATURE DISTRIBUTION IN THE RADIATION SECTION
C
C INPUT   :DIR,HRS,BR,WR,ATR,NR,LRB,TGO,EPSR,DELR,,WG,WGM
```

```
C OUTPUT :CTIR(NR),CTOR(NR),CPIR(NR),CPOR(NR),TSR(NR),TGR(NR),TGR(NR-1
C
C   CALCULATION OF VARIABLES USED AS CONSTANTS
      COMMON /A01/ RO1,W1,TFC,CBT
      COMMON /BI/  FOF,FOS,FOAPI,FGF,FGTI,FGPI,FGMC(11),AE,AH
      COMMON /B01/ WG,WGM,AFR
      COMMON /B02/ CON,HON,SON,ON,DNN
      COMMON /A02/ CM,GC
      COMMON /EI/  FOV,FOTI,STI,SPI,ATI,TO,PO
      COMMON /EO/  TF
      COMMON /GI/  DIR,ATR,ALRB,TLR,DOR
      COMMON /G02/ CTIR(25),CTOR(25),CPIR(25),CPOR(25),TSR(25),TGR(25)
      COMMON /A03/ CSG
      COMMON /AI1/ PT
      COMMON /AI2/ HRS,BR,WR,FL,NR
      COMMON /C02/ TGCO,CPRIC,CTRIC
      COMMON /G01/ GGR,AWR,ATER,TGR1,DIRS,ATRS
      COMMON /E01/ SW
      COMMON /FI1/ PL
      COMMON /G06/ JR
      COMMON /GT6/ QT
      COMMON /G08/ XJC(25),HVC
C
      EPSR =10.
      AWR  = 2.* HRS* (BR + WR)- NR * ATR
      ATTR= ATR *( NR + 3 ) * 2.
      ATER = ATTR + AWR
      ABR  = BR * WR
      GGR  = WG * WGM * 2.2046226 / ABR
      PP   = PT * ( CON + HON)
      PL   = ALRB * PP
      DIRS = DIR * 0.3048
      ATRS = ATR * 0.0929
C
      CALL ADIAF
C
C   TEMPERATURE DISTRIBUTION IN THE RADIATION SECTION
C
      TGR1= 1800.
C
   1  CALL RSINPH
      IF ( JR .EQ . NR+1 ) GO TO 8
C
      CALL RTWOPH
C
      CALL RCEILI
C
      TGRNR=TGR(NR+1)
    8 IF ( ABS(TGR(NR+1)-TGCO) .LE. EPSR ) GO TO 5
      TGR1= TGR1 -(TGR(NR+1)-TGCO) *2.5
      GO TO 1
C
    5 RETURN
      END
```

```
C
C
C
C-------------------------------------------------------------
C    CCCCC  PPPPP  GGGGG  I  TTTTT
C    C      P   P  G      I    T
C    C      PPPPP  GGGGG  I    T
C    CCCCC  P      GGGGG  I    T
C-------------------------------------------------------------
C
C
C
      FUNCTION CPGIT(T)
C
C CALCULATES THE HEAT CAPACITY FOR FLUE GAS (KCAL/KMOLE-K)
C
C INPUT:CON,HON,SON,ON,DNN
C
      COMMON /B02/ CON,HON,SON,ON,DNN
C
      A= 6.393 * CON + 6.529 * DNN + 6.732 * ON + 6.970 * HON + 9.299*S
      B= 10.10 * CON + 1.488 * DNN + 1.505 * ON + 3.464 * HON
      C= 3.405 * CON + 0.227 * DNN + 0.179 * ON + 0.483 * HON
      TC = T -273.
      CPGIT= A   + B * T / 1000.+ C * (T**2.)/1E+6+
     &        SON * (9.33E-3 * TC -7.4187E-6 * TC2**2.+2.057E-9*TC**3.)
      RETURN
      END
C
C
C
C-------------------------------------------------------------------
C        A    DDD   I    A    FFFFF  TTTTT
C       A A   D  D  I   A A   F        T
C      AAAAA  D  D  I  AAAAA  FFFF     T
C      A   A  DDD   I  A   A  F        T
C-------------------------------------------------------------------
C
C
C
      SUBROUTINE ADIAFT
C
C FINDS THE ADIABATIC FLAME TEMPRATURE OF COMBUSTION
C
C INPUT: FOAPI,FOV,FOTI,SW,STI,SPI,FGF,FGTI,FGPI,FGMC,ATI,TO,PO,EPSA,
C        DELA,WG,AFR,FOF
C OUTPUT: TF
C
      COMMON /BI/  FOF,FOS,FOAPI,FGF,FGTI,FGPI,FGMC(11),AE,AH,FGSG
      COMMON /B01/ WG,WGM,AFR
      COMMON /B02/ CON,HON,SON,ON,DNN
      COMMON /EI/  FOV,FOTI,STI,SPI,ATI,TO,PO
C      COMMON /EO/  TF
      COMMON /E01/ SW
```

```
      COMMON /E02/ QT
C
      FOSG = 141.5/ (131.5 + FOAPI)
      FOW  = FOF * 60. * FOSG
C
C  HEAT OFCOMBUSTION OF FUEL (KCAL/HR)
C
      QCFO = FOW * (12400.- 2100.* FOSG * FOSG)
      QCFG = FGF * (595.* FGMC(1) + 275.* FGMC(2) + 321.* FGMC(6) +
     &              911.* FGMC(7) + 0.5 * ((1622.+ 1503.) * FGMC(8) +
     &              (2322.+2188.) * FGMC(10) + (3009. + 2868.) * FGMC(
     &              ))) * 252.16 / 28.316
C  SENSIBLE HEAT OF INPUTS (KCAL/HR)
C
C   SENSIBLE HEAT OF AIR (KCAL/HR)
C
      QSA  = AFR * (6.173 * (ATI - TO)+ 0.04697 * (ATI * ATI -TO * TO)
     &              / 200.+ 0.1147 * (ATI**3. - TO**3.) /3E+5 -0.4696
     &              * (ATI**4. - TO**4.) / 4E+9 )
C
C   SENSIBLE HEAT OF STEAM (KCAL/HR)
C
      HSI  = HSTEAM (STI,SPI)
      QSS  =SW * HSI
C
C   SENSIBLE HEAT OF FUEL OIL (KCAL/HR)
C
      FOK  = PFKVAL(FOV,FOAPI)
C
      TOF  = (TO - 273.) * 1.8 + 32.
      TIF  = (FOTI - 273.) * 1.8 + 32.
      QSFO = FOW * 2.2046226 * 0.25216 * ((0.6811 - 0.308 * FOSG) *
     &             (TIF -TOF) + (0.815 - 0.306 * FOSG) * (TIF*TIF -
     &             TO*TO) / 2000.)* (0.055 * FOK + 0.35)
C
C   SENSIBLE HEAT OF FUEL GAS
C
      TOC  = TO - 273.
      TIC  = FGTI - 273.
      FGM  = FGPI * FGF / (FGTI * 0.0820567)
      QSFG = FGM* ( FGMC(5) * (1.01 * (FGTI*FGTI - TO*TO) / 200. -
     &      0.1134E-5 * (FGTI**3. -TO**3.)) + (TIC-TOC) * (8.010
     &      * FGMC(1) + 6.702 * FGMC(2) + 6.919 * FGMC(3) + 7.129
     &      * FGMC(4) + 6.393 * FGMC(5) + 6.890 * FGMC(6) + 8.200
     &      * FGMC(7) + 11.77 * FGMC(8) + 15.25 * FGMC(9) +20.596
     &      * FGMC(10)+20.985 * FGMC(11))+0.005 *(TIC*TIC-TOC*TOC)
     &      * (0.370 * FGMC(1) + 0.099 * FGMC(2) + 0.136 * FGMC(3)
     &      + 0.141 * FGMC(4) + 0.144 * FGMC(6) + 1.307 * FGMC(7)
     &      + 3.034 * FGMC(8) + 4.815 * FGMC(9) +  6.665 * FGMC(10)
     &      + 6.396 * FGMC(11))  + (TIC**3. - TOC**3.) / 3E+7 *
     &      ( 7.200 * FGMC(1) - 0.780 * FGMC(2) -  2.271 * FGMC(3)
     &       - 1.791 * FGMC(4) -  2.387 * FGMC(6) + 8.750 * FGMC(7)
     &       - 156.9 * FGMC(8) - 278.2 * FGMC(9) -  432.3 * FGMC(10)
     &       - 391.2 * FGMC(11))  + (TIC**4. - TOC**4.) / 4E+9 *
```

```
     &       (- 0.787 * FGMC(1) - 2.630 * FGMC(7) +  2.980 * FGMC(8)
     &    + 6.730 * FGMC(9) + 11.995 * FGMC(10)+ 10.215 * FGMC(11)))
C
C  TOTAL HEAT INPUT (KCAL/HR)
C
      QC    = QCFO + QCFG
      QS   = QSA+ QSS + QSFO + QSFG
      QT   = QC + QS
C  ITARATIVE CALCULATION OF ADIABATIC FLAME TEMPERATURE TF('K)
       EPSA =1000.
       DELA =.001
C
C   INITIAL GUESS FOR TF
C
       TF   = 1610.72
C
C   CALCULATION OF TF
C
C    1 HG   = WG * CPGI(TO,TF)
C      IF ( ABS(QT-HG) .LE. EPSA ) GO TO 3
C      IF ( HG .GT. QT ) GO TO 2
C      TF   = TF + DELA
C      GO TO 1
C    2 TF   = TF - DELA
C      GO TO 1
C    3 HEATOUT= WG * CPGI(TO,TF)
C      ERROR = HEATOUT-QT
C
      RETURN
      END
C
C
C
C--------------------------------------------------------------------------
C     PPPPP  RRRRR   I  N    N  TTTTT  OOOOO
C     P   P  R   R   I  N  N N    T    O   O
C     PPPPP  RRRR    I  N   NN    T    O   O
C     P      R   R   I  N    N    T    OOOOO
C--------------------------------------------------------------------------
C
C
C
      SUBROUTINE PRINTO
C
C THIS SUBROUTINE PRINTS THE OUTPUT OF THE FURNACE PROGRAM
C
      COMMON /A01/ RO1,W1,TFC,CBT
      COMMON /A02/ CM,GC
      COMMON /A03/ CSG
      COMMON /B01/ WG,WGM,AFR
      COMMON /B02/ CON,HON,SON,ON,DNN
      COMMON /C05/ CTIC(7,2),CTOC(7,2),CPIC(7,2),CPOC(7,2),
     &             TSC(7,2),TSAC(7),TGC(7)
      COMMON /EO/  TF
```

```
      COMMON /E01/ SW
      COMMON /C03/ SL,GG,AW,ATE
      COMMON /G01/ GGR,AWR,ATER,TGR1,DIRS,ATRS
      COMMON /G02/ CTIR(25),CTOR(25),CPIR(25),CPOR(25),
     &             TSR(25),  TGR(25)
      COMMON /G08/ XJC(25)
      COMMON /E02/ QT
      COMMON /ERR/ QGAS,QCHARGE,ERROR,ERROR1
C
C
      WRITE (9,1) CM,GC,CSG,R01,TFC,CBT
    1 FORMAT (H,/////,10X,'OUTPUT OF THE FURNACE PROGRAM',
     &         /,10X,29('_'),///,10X,'INPUT VARIABLES OF CHARGE:'
     &    ,/,28X,'MASS FLOW = ',F15.7,'Kg/hr',/,28X,'MASS FLOW
     &RATE = ',F15.7,'Lb/hr-ft**2',/,28X,'SPECIFIC GRAVITY = '
     &         ,F6.5,/,28X,'DENSITY AT 60F = ',F10.5,'Lb/ft**3',
     &        /,28X,'CRITICAL TEMPERATURE = ',F8.3,'F',/,28X,
     &         'BOILING TEMPERATURE AT 1 Atm = ',F8.3,'F')
C
      WRITE (9,2) SW,AFR,WG,WGM,CON,HON,SON,ON,DNN,TF
    2 FORMAT (///,10X,'RESULTS OF MASS BALANCE: ',3X,'MASS FLOW OF
     &STEAM = ',F10.5,'Kg/hr',/,36X,'MOLAR FLOW OF AIR = ',F12.5,
     &         'Kmole/hr',/,36X,'MOLAR FLOW OF FLUE GAS = ',F12.5,
     &         'Kmole/hr',/,36X,'MOLECULAR WEIGHT OF FLUE GAS = ',
     &         F10.6,/,36X,'MOLE FRACTION OF COMPONENTS OF FLUE GAS:
     &  C02 = ',F6.5,/,78X,'H20 = ',F6.5,/,78X,'S02 = ',F6.5,/,78X,
     &         '02 = ',F6.5,/,78X,'N2 = ',F6.5,/,78X,///,10X,
     &         'RESULT OF ENERGY BALANCE : ',3X,'ADIABATIC FLAME
     &TEMPERATURE = ',F7.2,'K' )
C
      WRITE (9,3) AW,ATE,GG
    3 FORMAT (///,10X,'RESULTS OF CONVECTION SECTION : ',/,39X,
     &          'WALL AREA = ',F10.5,'Ft**2',/,39X,'TOTAL EXCHANGE
     &AREA = ',F10.5,'Ft**2',/,39X,'FLUE GAS MASS FLOW RATE = ',
     &         F10.5,'Lb/hr-ft**2',//,39X,'TEMPERATURE(K) DISTRIBUTION'
     &         ,/,10X,'# OF STAGE',9X,'CHARGE INLET TEMP',11X,
     &         'CHARGE OUTLET TEMP',9X,'CHARGE OUTLET PRES.',8X,
     &         'FLUE GAS TEMP',/,31X,'M=1',8X,'M=2',14X,'M=1',8X,
     &         'M=2',14X,'M=1',8X,'M=2')
C
      DO 9 J=1,7
       WRITE (9,4)(J,(CTIC(J,I),I=1,2),(CTOC(J,I),I=1,2),
     &                 (CPOC(J,I),I=1,2), TGC(J))
    4 FORMAT(/,14X,I2,12X,2F10.5,8X,2F10.5,8X,2F10.7,8X,F10.5,/)
    9 CONTINUE
C
      WRITE (9,5) AWR,ATER,GGR
    5 FORMAT (///,10X,'RESULTS OF RADIATION SECTION : ',/,39X,
     &          'WALL AREA = ',F10.5,'Ft**2',/,39X,'TOTAL EXCHANGE
     &AREA = ',F10.5,'Ft**2',/,39X,'FLUE GAS MASS FLOW RATE = ',
     &         F10.5,'Lb/hr-ft**2',//,39X,'TEMPERATURE(K) DISTRIBUTION'
     &         ,/,1X,'# OF STAGE',2X,'CHARGE INLET TEMP',3X,
     &         'CHARGE OUTLET TEMP',3X,'TUBE SURFACE TEMP',5X,
     &         'FLUE GAS TEMP',3X,'CHARGE OUTLET PRES',2X,'VAPOR
     & FRACTION')
```

```
      DO 8 I=1,25
      WRITE (9,6) I,CTIR(I),CTOR(I),TSR(I),TGR(I),CPOR(I),XJC(I)
    6 FORMAT(/,5X,I2,6(10X,F10.5),/)
    8 CONTINUE
C
      WRITE (9,7) QT,QGAS,QCHARGE,ERROR,ERROR1
    7 FORMAT (///,10X,'RESULT OF OVERALL ENERGY BALANCE:',/,
     &        39X,'HEAT INPUT (kcal/hr) = ',F20.10,/,
     &        39X,'HEAT GIVEN BY GAS (kcal/hr) = ',F20.10,/,
     &        39X,'HEAT TAKEN BY CHARGE (kcal/hr) = ',F20.10,/,
     &        39X,'%ERROR BETWEEN QGAS & QCHARGE = ',F6.3,/,
     &        39X,'%ERROR BETWEEN HEAT INPUT & QGAS = ',F6.3,/)
C
      RETURN
      END
C
C
C
C---------------------------------------------------------------
C    CCCCC  PPPPP  GGGGG   I
C    C      P   P  G       I
C    C      PPPPP  GGGGG   I
C    CCCCC  P      GGGGG   I
C---------------------------------------------------------------
C
C
C
      FUNCTION CPGI(T1,T2)
C
C CALCULATES THE INTEGRATED HEAT CAPACITY FOR FLUE GAS (KCAL/HR)
C
C INPUT:CON,HON,SON,ON,DNN
C
      COMMON /B02/ CON,HON,SON,ON,DNN
C
      A= 6.393 * CON + 6.529 * DNN + 6.732 * ON + 6.970 * HON + 9.299*SC
      B= 10.10 * CON + 1.488 * DNN + 1.505 * ON + 3.464 * HON
      C= 3.405 * CON + 0.227 * DNN + 0.179 * ON + 0.483 * HON
      TC1 = T1 -273.
      TC2 = T2 -273.
      CPGI= A * (T2- T1) + B * (T2*T2 - T1*T1) / 2000.+ C * (T2**3.-
     &          T1**3.) / 3E+6 + SON * (4.665E-3 * (TC2*TC2 - TC1*TC1)
     &                                -2.47267E-6 * (TC2**3.- TC1**3.)
     &                                +5.1425E-10 * (TC2**4.- TC1**4.))
C
      RETURN
      END
C
C
C
C------------------------------------------------------------------
C         CCCCC  PPPPP  CCCCC  L
C         C      P   P  C      L
C         C      PPPPP  C      L
C         CCCCC  P      CCCCC  LLLLL
C------------------------------------------------------------------
```

```
C
C
C
      FUNCTION CPCL ( T )
C
C FINDS THE LIQUID PHASE SPECIFIC HEAT PETROLEUM FRACTIONS(BTU/LB-F=
C                                                            KCAL/KG-
C  INPUT : SG,K
C
      COMMON /A03/ CSG
      COMMON /AI3/ DI,CK,CAPI,CF
C
      TF   = (T - 273.) * 1.8 + 32.
      CPCL = ((0.6811 - 0.308 * CSG) +TF *1.E-4 *(8.15 - 3.06 * CSG))*
     &                                          (0.055 * CK + 0.35)
C
      RETURN
      END
C
C
C
C-------------------------------------------------------------------
C          V     V  CCCCC  CCCCC
C           V   V   C      C
C            V V    C      C
C             V     CCCCC  CCCCC
C-------------------------------------------------------------------
C
C
C
      FUNCTION VCC (T)
C
C     FINDS THE LIQUID PHASE VISCOSITY OF PETROLEUM FRACTIONS
C
C     INPUT : V1,V2,TC1,TC2
C
      COMMON /H/ V1,V2,TC1,TC2
C
      DIMENSION Z(2),V(2),C(2),D(2),E(2),F(2),G(2),H(2)
      CN(VV) = EXP ( -1.14883 - 2.65868 * VV )
      DN(VV) = EXP ( -0.00381308 - 12.5645 * VV )
      EN(VV) = EXP ( 5.46491 - 37.62898 * VV )
      FN(VV) = EXP ( 13.0458 - 74.6851 * VV )
      GN(VV) = EXP ( 37.4619 - 192.643 * VV )
      HN(VV) = EXP ( 80.4945 - 400.468 * VV )
      FF(VV) = VV - ZN + 0.7 + CN(VV) - DN(VV) + EN(VV) - FN(VV) +
     &                        GN(VV) - HN(VV)
      DD(VV)=1.- 2.65868 * CN(VV)+12.5645 * DN(VV) -37.62898 * EN(VV)
     &          + 74.6851 * FN(VV) - 192.643 * GN(VV) + 400.468 * HN(VV
C
      V(1) = V1
      V(2) =V2
C
      DO 1 I = 1,2
```

```
      C(I) = EXP ( -1.14883 - 2.65868 * V(I) )
      D(I) = EXP ( -0.00381308 - 12.5645 * V(I) )
      E(I) = EXP ( 5.46491 - 37.62898 * V(I) )
      F(I) = EXP ( 13.0458 - 74.6851 * V(I) )
      G(I) = EXP ( 37.4619 - 192.643 * V(I) )
      H(I) = EXP ( 80.4945 - 400.468 * V(I) )
      Z(I) = V(I) + 0.7 + C(I) - D(I) + E(I) - F(I) + G(I) - H(I)
    1 CONTINUE
C
      B     = (ALOG10( ALOG10 (Z(1) )) - ALOG10 (ALOG10 ( Z(2))))/
     &        ( ALOG10 ( TC2 ) - ALOG10 ( TC1 ) )
      A     = B * ALOG10 (TC1) + ALOG10 ( ALOG10 ( Z(1) ) )
      EPSV =.02
      ZN    = 10. ** ( 10. ** ( A - B * ALOG10 ( T ) ) )
      VB    = ZN + 0.7
    2 VY     = VB - FF(VB) / DD(VB)
      IF ( ABS ( VB - VY ) .LE. EPSV ) GO TO 5
      VB     = VY
      GO TO 2
    5 VCC    = VY * 36 * 0.0010764 * ROCL(T)
C
      RETURN
      END
C
C
C
C--------------------------------------------------------------
C           H   H  I
C           H   H  I
C           HHHHH  I
C           H   H  I
C--------------------------------------------------------------
C
C
C
      FUNCTION HI ( VC,T,DI )
C
C FINDS THE CONVECTIVE HEAT TRANSFER COEFF. FOR THE TUBE SIDE (KCAL/
C                                                              HR-K-M**
C INPUT : TCL,DI,VC,CPCL,GC
C
      COMMON /A02/ CM,GC
C
      PR = VC* CPCL (T)  / TCL (T)
      RE = DI * GC / VC
      HI = 0.075681377* TCL(T) * ( PR**0.5 ) * ( RE**0.83 ) / DI
C
      RETURN
      END
C
C
C
```

```
C-----------------------------------------------------------------------
C                    TTTTT  CCCCC  L
C                      T    C      L
C                      T    C      L
C                      T    CCCCC  LLLLL
C-----------------------------------------------------------------------
C
C
C
      FUNCTION TCL(T)
C
C
C FINDS LIQUID PHASE THERMAL CONDUCTIVITY OF PETROLEUM FRACTIONS (BTU/
C                                                                   HR-FT-
C INPUT : SG
      COMMON /A03/CSG
C
      TF  = (T-273.) *1.8 + 32.
      TCL = 0.06775 * (1.- 0.0003 * (TF - 32)) /CSG
C
      RETURN
      END
C
C
C
C-------------------------------------------------------------------
C               FFFFF  FFFFF  CCCCC
C               F      F      C
C               FFF    FFF    C
C               F      F      CCCCC
C-------------------------------------------------------------------
C
C
C
      FUNCTION FFC( VC,DIC )
C
C FINDS FRICTION FACTOR FOR LIQUIDS WITH VERY HIGH REYNOLDS NUMBER
C
C  INPUT :DIC,GC,VC,EPSF,DELF
C
      COMMON /A02/ CM,GC
C
      FX (F) = 0.87 * LOG ( RE * 2.* ( F**0.5) ) - 0.5 / ( F ** .5 )- 0.
      T (F) = 0.87 / (2. * F ) + 0.25 / F ** 1.5
      RE = DIC * GC / VC
      FF = 0.0046 / (RE**0.2)
      EPSF = FF * 0.02
    9 FY     = FF - FX (FF)/ T(FF)
      IF ( ABS(FF - FY ) .LE. EPSF ) GO TO 8
      FF = FY
      GO TO 9
    8 FFC= FY
C
      RETURN
      END
```

```
C
C
C
C-----------------------------------------------------------
C         RRRRR  00000  CCCCC  L
C         R   R  0   0  C      L
C         RRRRR  0   0  C      L
C         R  RR  00000  CCCCC  LLLLL
C-----------------------------------------------------------
C
C
C
      FUNCTION ROCL(T)
C
C  FINDS THE LIQUID PHASE DENSITY OF PETROLEUM FRACTIONS (LB/FT**3)
C
C  INPUT : R01,W1,TFC
C
      COMMON /A01/ R01,W1,TFC,CBT
      TF   = (T - 273.) * 1.8 + 32.
      TR   = TF / TFC
      W    = 0.1745 - 0.0838 * TR
      ROCL = R01 * W / W1
C
      RETURN
      END
C
C
C
C----------------------------------------------------------------
C            H   H  00000
C            H   H  0   0
C            HHHHH  0   0
C            H   H  00000
C----------------------------------------------------------------
C
C
C
      FUNCTION HO ( TG,TS,GG,DO,AW,AT )
C
C  FINDS THE HEAT TRANSFER COEFF. FROM FLUE GAS TO TUBE WALLS (KCAL/
C                                                               HR-K-M**
C  INPUT:GG,DO,AW,AT
C
      TGF = (TG - 273.) * 1.8 + 32.
      TSF = (TS - 273.) * 1.8 + 32.+460.
      HC  = 1.6*((GG/3600.)**(2./3.))*(TGF**0.3)/((DO*12.)**(1./3.))
      HR  = 0.0025 * TGF - 0.5
      HB  = 0.006536 * ((TSF/100.)**3.)
      RW  = AW * HB / ((HB + HC + HR) * AT)
      HO  = (1.+ RW) * (HC + HR) * 4.88556
C
      RETURN
      END
```

```
C
C
C
C------------------------------------------------------------------
C      RRRRR  SSSSS   I  N    N  PPPPP  H   H
C      R   R  S       I  N N  N  P   P  H   H
C      RRRRR  SSSSS   I  N  N N  PPPPP  HHHHH
C      R  RR  SSSSS   I  N    N  P      H   H
C------------------------------------------------------------------
C
C
C


      SUBROUTINE RSINPH
C
C
C FINDS THE TEMPERATURE DISTRIBUTION IN THE RADIATION SECTION WHERE
C THE CHARGE FLOWS ONLY IN THE LIQUID PHASE
C
C INPUT :TGR(1),CM,GC,TF,WG,CTIR(1),CPIR(1),KSIRS,EPSRS,DELRS,ATR,J,
C        DIR,LR,EPS2
C OUTPUT:CTIR(NR),CTOR(NR),CPIR(NR),CPOR(NR),TSR(NR),TGR(NR),TGR(NR-1
C
      DIMENSION Z(25),TGRN(25),TG(25),C(6),ALEV(25),FLAME(25)
C
      COMMON /A01/ R01,W1,TFC,CBT
      COMMON /B01/ WG,WGM,AFR
      COMMON /B02/ CON,HON,SON,ON,DNN
      COMMON /A02/ CM,GC
      COMMON /E0/  TF
      COMMON /GI/  DIR,ATR,ALRB,TLR,DOR
      COMMON /G02/ CTIR(25),CTOR(25),CPIR(25),CPOR(25),TSR(25),TGR(25)
      COMMON /A03/ CSG
      COMMON /AI2/ HRS,BR,WR,FL,NR
      COMMON /C02/ TGCO,CPRIC,CTRIC
      COMMON /FI1/ PL
      COMMON /G01/ GGR,AWR,ATER,TGR1,DIRS,ATRS
      COMMON /G03/ CTIRT,CPIRT,TGRT,JT,ZT,CBTP,TSRT,ALEVT
      COMMON /G04/ XSIRS,EPSRS,EPS2
      COMMON /G06/ JR
      COMMON /AI3/ DI,CK,CAPI,CF
      COMMON /GT6/ QT
C
      XSIRS =1.
      EPS2 =15.
      EPSRS =1.
      Z(1) = 40.
      J    = 2
      CTIR (J) = CTRIC
      CPIR (J) = CPRIC
      TGR  (1)  = TGR1
      ALEV(1)=0.
C
C   CALCULATION OF TEMPERATURE & PRESSURE
```

```
C
    1 Z(J)     = Z(J-1) - XSIRS
      TGR(J)   = TGR(J-1) - Z(J)
    2 TGAR     = (TGR(J) + TGR(J-1)) / 2.
      QGR      = WG* CPGI(TGR(J),TGR(J-1))
      CTIRF    = (CTIR(J) - 273.) * 1.8 + 32.
      CTOR(J)  = CTIR(J) + QGR/(2.* CM * CPCL(CTIR(J)))
      CTBR     = (CTOR(J)+ CTIR(J)) / 2.
      VC       =  VCC(CTBR)
      TSR(J)   = CTBR + QGR/(2.* DIRS*TLR*4.* ATAN(1.) *
     &                        HI ( VC,CTBR,DIR ))
      CPOR(J)  = CPIR(J)-(2.*(TLR+25.*DIRS)*GC*GC*0.015/
     &                (DIRS * ROCL(CTBR))) * 1.1332335E-12
      TFG=(TGAR-273.)*1.8+32.
      EF = -9.72222E-5*(TFG-2000.)+.458
      SFFSR    = SFFS (J)
      FAY      = EF * SFFSR
      SIGMA=5.6696E-8*3600./4186.8
      RAD= SIGMA*(TF**4. -TSR(J)**4.) * FAY
      TGRN(J)=2.*TSR(J)-TGR(J-1)+(QGR/ATRS-RAD)/
     &         HO(TGAR,TSR(J),GGR,DOR,AWR,ATER)
      FLAME(J)=RAD*ATRS
      ALEV(J)=ALEV(J-1)+FLAME(J)
      BINC=.01
      IF ( ABS(TGRN(J)-TGR(J)) .LE. EPSRS ) GO TO 3
      TGR(J) = TGR(J)+BINC*(TGRN(J)-TGR(J))
      GO TO 2
    3 IF (CPOR(J).LE. 0.)GO TO 33
      F        = 0.12906 * ALOG10(1./CPOR(J)) + 0.99316
      Y        = 106.46313 *ALOG10(1./CPOR(J)) + 4.2952
      CBTP     = ((CBT - Y) / F -32.) / 1.8 + 273
      IF ( ABS(CTOR(J) - CBTP) .LE. EPS2 ) GO TO 6
   33 J        =J + 1
      CTIR(J)=CTOR(J-1)
      CPIR(J)=CPOR(J-1)
      IF (J .GT. NR ) GO TO 5
      GO TO 1
    6 CTIRT = CTOR(J)
      CPIRT = CPOR(J)
      TSRT  = TSR(J)
      TGRT  = TGR(J)
      ALEVT=ALEV(J)
      JT=J
      ZT    = Z(J)
      JR    = J
      GO TO 10
    5 Z(J)     = Z(J-1) - XSIRS
      TGR(J)   = TGR(J-1) -5.* Z(J)
    4 TGAR     = (TGR(J) + TGR(J-1)) / 2.
      QGR      = WG* CPGI(TGR(J),TGR(J-1))
      CTIRF    = (CTIR(J) - 273.) * 1.8 + 32.
      CTOR(J)  = CTIR(J)+QGR/(6.* CM* CPCL(CTIR(J)))
      CTBR     = (CTOR(J)+ CTIR(J)) / 2.
      VC       =  VCC(CTBR)
```

```
      TSR(J)   = CTBR+QGR/ (6.* DIRS * TLR * 4.* ATAN(1.) *
     &                          HI ( VC,CTBR,DIR ))
      TFG=(TGAR-273.)*1.8+32.
      EF = -9.72222E-5*(TFG-2000.)+.458
      SUM      = 0.
      C(1)     = 0.
      DO 7 I   = 2,4
      C(I)     = C(I-1) + WR / 6.
      SUM      = SUM + SFCFS(C(I))
    7 CONTINUE
      FAY      = EF * SUM / 15.
      RAD= SIGMA*(TF**4. -TSR(J)**4.) * FAY
      TGRN(J)=2.*TSR(J)-TGR(J-1)+(QGR/(3.*ATRS)-RAD)/
     &         HO(TGAR,TSR(J),GGR,DOR,AWR,ATER)
      FLAME(J)=RAD*ATRS
      ALEV(J)=ALEV(J-1)+FLAME(J)
      IF ( ABS(TGRN(J) - TGR(J)) .LE. EPSRS ) GO TO 9
      TGR(J) = TGR(J)+BINC*(TGRN(J)-TGR(J))
      GO TO 4
    9 JR     = J
      TGR(J+1) = TGR(J)
   10 RETURN
      END
C
C
C
C-------------------------------------------------------------
C      SSSSS  FFFFF  FFFFF  SSSSS
C      S      F      F      S
C      SSSSS  FFF    FFF    SSSSS
C      SSSSS  F      F      SSSSS
C-------------------------------------------------------------
C
C
C
      FUNCTION SFFS(S)
C
C
C  FINDS THE SHAPE FACTOR BETWEEN FLAME & TUBES ON THE WALLS
C
C  INPUT:C=WR/2,B=BR,FL,A=HRS/NR
C
      COMMON /AI2/HRS,BR,WR,FL,NR
C
      C = WR/2.
      B= BR
      A=HRS/NR
      T  = C * C / (4.*ATAN(1.) * B * FL)
      A1 = S * A
      A2 = FL - S * A
      A3 = (S - 1.) * A
      A4 = FL - (S - 1.) * A
      A5 = ( C * C + (S * A)* (S * A)) ** 0.5
      A6 = ( C * C + (FL - S * A) * (FL - S * A)) ** 0.5
```

```
      A7 = ( C * C + ((S-1.) * A) * ((S-1.) * A)) ** 0.5
      A8 = ( C * C + (FL - (S-1.) * A) * (FL - (S-1.) * A)) ** 0.5
      D  = ((B * B) + (C * C)) ** 0.5
      E  = ((B * B) + (C * C)) ** 0.5/ (C * C)
      SFFS = T * ( 1./ C * ( A2 * ATAN(A2/C) - A1 * ATAN(A1/C) +
     &                        A3 * ATAN(A3/C) - A4 * ATAN(A4/C) )
     &                - E * ( A2 * ATAN(A2/D) - A1 * ATAN(A1/D) +
     &                        A3 * ATAN(A3/D) - A4 * ATAN(A4/D) )
     &         - B / (C*C) * (A6 * ATAN(B/A6) - A5 * ATAN(B/A5) +
     &                        A7 * ATAN(B/A7) - A8 * ATAN(B/A8) )
     &            + 0.5 * (ALOG(((A5 * A8 / (A6 * A7)) ** 2.) *
     &                        ((A6 ** 2.+ B * B) * (A7 ** 2.+ B * B)/
     &                        ((A5 **2.+ B * B) * (A8 ** 2.+ B * B))))))
C
      RETURN
      END
C
C
C
C--------------------------------------------------------------
C       SSSSS  FFFFF  CCCCC  FFFFF  SSSSS
C       S      F      C      F      S
C       SSSSS  FFF    C      FFF    SSSSS
C       SSSSS  F      CCCCC  F      SSSSS
C--------------------------------------------------------------
C
C
C
      FUNCTION SFCFS (C)
C
C
C  FINDS SHAPE FACTOR BETWEEN FLAME & TUBES ON THE CEILING
C
C  INPUT: A=HRS,B=BR,FL,C=HORIZONTAL DISTANCE BTW. FLAME & STAGE
C
      COMMON /AI2/HRS,BR,WR,FL,NR
C
      A = HRS
      B = BR
      DOR=.7188
      T = C* DOR/ (FL*4.* ATAN(1.))
      D = (A -FL) ** 2.
      U = 1./ (2. * B)
      E = (D + C * C) ** 0.5
      F = (A * A + C * C) ** 0.5
      SECFS = T * ( U * ALOG((A * A + B * B + C * C ) * (D + C * C) /
     &                     ((A * A + C * C ) * (D + C * C + B * B))) -
     &                   ATAN(B / F) / F + ATAN(B / E) / E)
C
      RETURN
      END
C
C
C
```

```
C--------------------------------------------------------
C      RRRRR TTTTT W   W 000000 PPPPP H   H
C      R   R   T   W W W 0    0 P   P H   H
C      RRRRR   T   WW WW 0    0 PPPPP HHHHH
C      R  RR   T   W   W 000000 P     H   H
C--------------------------------------------------------
C
C
C
      SUBROUTINE RTWOPH
C
C
C FINDS THE TEMPERATURE DISTRIBUTION IN THE RADIATION SECTION WHERE
C THE CHARGE FLOWS IN TWO PHASE ,LIQUID AND GAS
C
C INPUT :
C
C OUTPUT:CTIR(J),CTOR(J),CPIR(J),CPOR(J),TSR(J),TGR(J),TGR(J-1)
C
      DIMENSION Z(25),TGRN(25),TG(25),X(25),ALEV(25),FLAME(25)
C
      COMMON /A01/ RO1,W1,TFC,CBT
      COMMON /B01/ WG,WGM,AFR
      COMMON /B02/ CON,HON,SON,ON,DNN
      COMMON /A02/ CM,GC
      COMMON /E0/  TF
      COMMON /GI/  DIR,ATR,ALRB,TLR,DOR
      COMMON /G02/ CTIR(25),CTOR(25),CPIR(25),CPOR(25),TSR(25),TGR(25)
      COMMON /A03/ CSG
      COMMON /AI2/HRS,BR,WR,FL,NR
      COMMON /FI1/ PL
      COMMON /G01/ GGR,AWR,ATER,TGR1,DIRS,ATRS
      COMMON /G03/ CTIRT,CPIRT,TGRT,JT,ZT,CBTP,TSRT,ALEVT
      COMMON /G04/ XSIRS,EPSRS,EPS2
      COMMON /AI3/ DI,CK,CAPI,CF
      COMMON /G05/ CTIRC,CPIRC,ZC,TGRC,XC,TSRC,ALEVC
      COMMON /G08/ XJC(25),HVC
      COMMON /GH/  HITP
      COMMON /GT6/ QT
C
      SGC =ROCL(CTIRT)/62.37364867
      APIC=(141.5/SGC)-131.5
      CBTPF    = (CBTP - 273.) * 1.8 + 32.
      CKC =((CBTPF+460.)**(1./3.))/SGC
      CMW =ABS(CMWPF(APIC,CKC))
      CMWI =ABS(CMWPF(CAPI,CK))
      HVC1      = HVPF (CMWI,CBT)
      HVC2      = HVPF (CMW,CTIRT)
      HVC =60.21
      J = JT + 1
      Z(J-1) = ZT
      CTIR (J) = CTIRT
      TSR  (J-1)  = TSRT
      TGR  (J-1)  = TGRT
```

```
      X(J-1)=0.
      XJC(J-1) =0.
      ALEV(J-1)=ALEVT
C
C   CALCULATION OF TEMPERATURE & PRESSURE
C
    1 Z(J)    = Z(J-1) - XSIRS
      TGR(J)  = TGR(J-1) - Z(J)
    2 TGAR    = (TGR(J) + TGR(J-1)) / 2.
      QGR     = WG* CPGI(TGR(J),TGR(J-1))
      TYPE *,'QGR',QGR
      CTIRF   = (CTIR(J) - 273.) * 1.8 + 32.
      HIC     = (CTIR(J)-298.)*(CPCG(CTIR(J))* XJC(J-1) +
     &                          CPCL(CTIR(J))* (1.-XJC(J-1)))
      X(J)=( QGR/(2.*CM))/HVC
      XJC(J)=XJC(J-1) +X(J)
      XXJ=XJC(J)
      CTOR(J)= CTIR(J) +((   QGR / (2.* CM) - X(J) * HVC) /
     &                  ((1.-XJC(J))*CPCL(CTIR(J))
     &                         +XJC(J)*CPCG(CTIR(J))))
      CTBR    = (CTOR(J)+ CTIR(J)) / 2.
      VCL     =  VCC(CTBR)
      TSRJ1=TSR(J-1)
      CALL TPHTC(CTBR,CMW,XXJ,TSRJ1,HVC,CM,GC,CPIRT)
      TSR(J) = CTBR +QGR/(2.*DIRS *TLR * 4.* ATAN(1.) * HITP)
      TFG=(TGAR-273.)*1.8+32.
      EF = -9.72222E-5*(TFG-2000.)+.458
      SFFSR   = SFFS (J)
      FAY     = EF * SFFSR
      SIGMA=5.6696E-8*3600./4186.8
      RAD= SIGMA*(TF**4. -TSR(J)**4.) * FAY
      TGRN(J)=2.*TSR(J)-TGR(J-1)+(QGR/ATRS-RAD)/
     &         HO(TGAR,TSR(J),GGR,DOR,AWR,ATER)
      FLAME(J)=RAD*ATRS
      ALEV(J)=ALEV(J-1)+FLAME(J)
      BINC=.01
      IF ( ABS(TGRN(J)-TGR(J)) .LE. EPSRS ) GO TO 3
      TGR(J) = TGR(J)+BINC*(TGRN(J)-TGR(J))
      GO TO 2
    3 J       = J+1
      IF (J .GT. NR) GO TO 6
      CTIR(J)=CTOR(J-1)
      GO TO 1
    6 ZC =  Z(J-1)
      CTIRC = CTIR(J-1)
      TSRC  = TSR(J-1)
      TGRC  = TGR(J-1)
      XC = XJC(J-1)
      ALEVC=ALEV(J-1)
C
      RETURN
      END
C
C
```

```
C
C-----------------------------------------------------------------------
C     CCCCC  M   M  W   W  PPPPP  FFFFF
C     C      MM MM  W W W  P   P  F
C     C      M M M  WW WW  PPPPP  FFF
C     CCCCC  M   M  W   W  P      F
C-----------------------------------------------------------------------
C
C
C
      FUNCTION CMWPF(API,CK)
C
C  FINDS THE MOLECULAR WEIGHT OF PETROLEUM FRACTIONS
C
C  INPUT:CAPI,CK
C
      A = 33.14991 * COS( API/120 ) + 0.00107 * API * API - 32.37044
      B = 0.20814 + 1.E-5 * API *(-2391.69992 + 150.66076 * API -
     &          4.37442 * API * API + 0.05865 * API ** 3. - 2.9E-4
     &                                * API ** 4.)

      CMWPF = B * EXP(A * CK)
C
      RETURN
      END
C
C
C
C-----------------------------------------------------------------------
C     H   H  V   V  PPPPP  FFFFF
C     H   H  V   V  P   P  F
C     HHHHH   V V   PPPPP  FFF
C     H   H    V    P      F
C-----------------------------------------------------------------------
C
C
C
      FUNCTION HVPF(CMW,TB)
C
C  FINDS THE LATENT HEAT OF VAPORIZATION OF PETROLEUM FRACTIONS AT GIV
C  BOILING TEMPERATURE (KCAL/KG)
C
C  INPUT:CMW,TB
C
      HVPF = ( TB * (8.75 + 4.571 * ALOG10(TB))/CMW)
C
      RETURN
      END
C
C
C
C------------------------------------------------------------------
C         CCCCC  PPPPP  CCCCC  GGGGG
C         C      P   P  C      G
C         C      PPPPP  C      G GGG
C         CCCCC  P      CCCCC  GGGGG
C------------------------------------------------------------------
```

```
C
C
C
       FUNCTION CPCG(T)
C
C
C  FINDS THE GAS PHASE SPECIFIC HEAT OF PETROLEUM FRACTIONS
C                                                (BTU/LB-F=KCAL/KG-K)
C  INPUT: SG,K
C
       COMMON /A03/ CSG
       COMMON /AI3/ DI,CK,CAPI,CF
C
       TF = (T - 273.) * 1.8 + 32.
       CPCG = (4.0 - CSG ) * ( TF + 670.) * (0.12 * CK - 0.41) / 6450.
C
       RETURN
       END
C
C
C
C-----------------------------------------------------------------------
C         TTTTT  PPPPP  H   H  TTTTT  CCCCC
C           T    P   P  H   H    T    C
C           T    PPPPP  HHHHH    T    C
C           T    P      H   H    T    CCCCC
C-----------------------------------------------------------------------
C
C
C
      SUBROUTINE TPHTC(CTBR,CMW,XJC,TSRJ1,HVC,CM,GC,CPIRT)
C
C
C FINDS TWO PHASE HEAT TRANSFER COEFFICIENT FOR THE TUBE SIDE
C                                       (KCAL/HR-K-M**2)
C
C INPUT:CPIRT,CTBR,CMW,X(J),CM,DIRS,VCL,DIR,TSR(J),HVC,GC
C
      COMMON /A01/ RO1,W1,TFC,CBT
      COMMON /GI/  DIR,ATR,ALRB,TLR,DOR
      COMMON /GH/  HITP
C
C CALCULATION OF VOID FRACTION ALFA
C
      ALFA=1./(1.+((1.-XJC)/XJC)*(ROCG(CPIRT,CTBR)*CMW*0.062428/
     &             ROCL(CTBR)))
C
C CALCULATION OF THE PROPERTIES
C
      DIRS=DIR*.3048
      ROG = ROCG(CPIRT,CTBR)*CMW
      ROL = ROCL(CTBR)
      VCL = VCC(CTBR)
      VCG = 3.5E-3
```

```
      DRO = ROL-ROG*.062428
      STC = 9.
      CPL = CPCL(CTBR)
      CPG = CPCG(CTBR)
      TCCL= TCL(CTBR)
      TCCG= ABS(TCG(CTBR,CMW))
      ROA = 1.29
      ROW = .997*62.37364867
      VCA = .018
      VCW = 1.1*2.4223
      STW = 73.6
C
C CALCULATION OF SUPERFICIAL VELOCITIES (M/S)
C
      VELG=4.*(CM*XJC)/(3600.*ROG*DIRS*DIRS*4.*ATAN(1.))
      VELL=VELG*(1.-ALFA)/ALFA
C
C DETERMINATION OF THE FLOW PATTERN
C
      FX   =((ROG/ROA)**.333)*(((ROL/ROW)*(STW/STC))**.25)
     &        *((VCG/VCA)**.2)
      FY   =((VCL/VCW)**.2)*(((ROL/ROW)*(STW/STC))**.25)
      FVELL1=.1*FY
      FVELL2=4.*FY
      FVELG1=15.*FX
      FVELG2=FX*(.001+(VELL-.4)*.057457)
      IF ( VELL .GT.FVELL1) GO TO 1
      IF ( VELG .GT.FVELG1) GO TO 3
      GO TO 2
    1 IF ( VELG .GT.FVELG2) GO TO 3
      IF ( VELL .GT.FVELL2) GO TO 3
C
C THE TOP WALL OF THE TUBE IS DRY
C
    2 THETA=ALFA*180./(4.*ATAN(1.))
      AREA =((DIR/2.)**2.)*4.*ATAN(1.)
      DHG  =2.*(AREA*XJC/(4.*ATAN(1.)))**.5
      DHL  =2.*(AREA*(1.-XJC)/(4.*ATAN(1.)))**.5
      REL  =GC*(1.-XJC)*DHL/VCL
      PRL  =VCL*CPL/TCCL
      HIL  =0.07572618*TCCL*(PRL**.5)*(REL**.83)/DHL
      REG  =GC*XJC*DHG/(VCG*2.42)
      PRG  =VCG*2.42*CPG/TCCG
      HIG  =0.11236788*TCCG*(PRG**.4)*(REG**.8)/DHG
      RETP =(ROL*VELG*3600.*DHL/(.3048*ALFA))/VCL
      IF ( RETP .GT.5.E5) GO TO 5
      S =-.4669855+17.6252375*(RETP**(-.265))
      GO TO 9
    5 S    =0.075
    9 DTSAT=TSRJ1-CTBR
      TSF  =(TSRJ1-273.)*1.8+32.
      PS   =1./(10.**((((CBT-4.2952)/TSF)-0.99316)/
     &                (.12906 + (106.43313/TSF))))
      CBPR   =1./(10.**((((CBT-4.2952)/CTBR)-0.99316)/
     &                (.12906 + (106.43313/CTBR))))
```

```
      DPSAT=(PS-CBPR)*101325.
      HNUC =.00122*.859845227*(DTSAT**.24)*S*(DPSAT**.75)
     &       *((TCCL*1.731)**.79)*((4186.8*CPL)**.45)*
     &         ((ROL*16.018)**.49)/(((STC/1000.)**.5)*
     &         ((VCL*4.14E-4)**.29)*(ROG**.24)*((HVC*4186.8)
     &         **.24))
      HITP= THETA*HIG/(4.*ATAN(1.))+(HIL+HNUC)*(1.-(THETA/
     &      (4.*ATAN(1.))))
      GO TO 7
C
C TOP OF THE WALL IS WET.......CHEN CORRELATION
C
    3 XTTI=1./((((1.-XJC)/XJC)**.9)*((ROG/ROL*16.018)**.5)
     &        *((VCL/VCG*2.4223)**.1))
      FCC=.862888+1.426638*XTTI+.074524*XTTI**2.-
     &     .011958*XTTI**3.
      REL  =GC*(1.-XJC)*DIR/VCL
      PRL  =VCL*CPL/TCCL
      HMAC =0.023*4.88*TCCL*(PRL**.4)*(REL**.8)*FCC/DIR
      RETP =REL*(FCC**1.25)
      IF ( RETP .GT.5.E5) GO TO 15
      S =-.4669855+17.6252375*(RETP**(-.265))
      GO TO 19
   15 S    =0.075
   19 DTSAT=TSRJ1-CTBR
      TSF  =(TSRJ1-273.)*1.8+32.
      PS   =1./(10.**((((CBT-4.2952)/TSF)-0.99316)/
     &                (.12906 + (106.43313/TSF))))
      CBPR   =1./(10.**((((CBT-4.2952)/CTBR)-0.99316)/
     &                (.12906 + (106.43313/CTBR))))
      DPSAT=(PS-CBPR)*101325.
      HMIC =.00122*.859845227*(DTSAT**.24)*S*(DPSAT**.75)
     &       *((TCCL*1.731)**.79)*((4186.8*CPL)**.45)*
     &         ((ROL*16.018)**.49)/(((STC/1000.)**.5)*
     &         ((VCL*4.14E-4)**.29)*(ROG**.24)*((HVC*4186.8)
     &         **.24))
      HITP =HMIC+HMAC
C
    7 RETURN
      END
C
C
C
C------------------------------------------------------------------
C                TTTTT  CCCCC  GGGGG
C                  T    C      G
C                  T    C      G GGG
C                  T    CCCCC  GGGGG
C------------------------------------------------------------------
C
C
C
       FUNCTION TCG(T,CMW)
C
```

```
C  FINDS THE GAS PHASE THERMAL CONDUCTIVITY OF PETROLEUM FRACTIONS
C                                                           (BTU/HR-FT-
C  INPUT:CMW,TF
C
      TF = (T-273.) * 1.8 + 32.
      A  = 0.03790E-5 * CMW + 0.00026 *CMW ** (-0.31342) -
    &      6.E-5 -1.E-9* CMW**2.
      B  = 0.11260 * CMW ** (-0.47367)-0.00574 *SIN(CMW**.3)-0.01902
      TCG= A * TF + B
C
      RETURN
      END
C
C
C
C---------------------------------------------------------------
C           RRRRR  OOOOO  CCCCC  GGGGG
C           R   R  O   O  C      G
C           RRRRR  O   O  C      G GGG
C           R  RR  OOOOO  CCCCC  GGGGG
C---------------------------------------------------------------
C
C
C
      FUNCTION ROCG(P,T)
C
C  FINDS THE GAS PHASE DENSITY OF PETROLEUM FRACTIONS
C
C INPUT: P,T,R,TFC,CBT,R
C
      COMMON /A01/ R01,W1,TFC,CBT
C
C CALCULATION OF REDUCED PRESSURE
C
       A   = 0.37036E-5 * CBT * CBT + 4.09629
       B   = EXP(-3E-5 * CBT * CBT - 20.13179)
      PPC  = B * TFC ** A
      PR   = P * 14.696/PPC
C
C CALCULATION OF REDUCED TEMPERATURE
C
      TF   =(T-273.)*1.8 + 32.
      TR   =TF/TFC
C
C CALCULATION OF COMPRESSIBILITY FACTOR
C
      IF ( PR .LE.2) GO TO 1
      Z   = 1.0 - (0.24 - 0.14 * TR ) * (8-PR)
      GO TO 2
   1  Z   = 1.0 - (0.73* TR ** (-3.)-0.18)* PR
C
C  CALCULATION OF DENSITY
C
   2  ROCG = P / (Z * 0.08205 * T)
```

```
C
      RETURN
      END
C
C
C
C------------------------------------------------------------------
C      RRRRR  CCCCC  EEEEE   I  L      I
C      R   R  C      E       I  L      I
C      RRRRR  C      EEE     I  L      I
C      R  RR  CCCCC  EEEEE   I  LLLLL  I
C------------------------------------------------------------------
C
C
C
      SUBROUTINE RCEILI
C
C
C FINDS THE TEMPERATURE DISTRIBUTION IN THE RADIATION SECTION WHERE
C THE CHARGE FLOWS IN TWO PHASE ,LIQUID AND GAS,INSIDE THE CEILING TUBE
C
C INPUT :
C
C OUTPUT:CTIR(J),CTOR(J),CPIR(J),CPOR(J),TSR(J),TGR(J),TGR(J-1)
C
      DIMENSION Z(25),TGRN(25),TG(25),C(6)
C
      COMMON /A01/ R01,W1,TFC,CBT
      COMMON /B01/ WG,WGM,AFR
      COMMON /B02/ CON,HON,SON,ON,DNN
      COMMON /A02/ CM,GC
      COMMON /E0/  TF
      COMMON /GI/  DIR,ATR,ALRB,TLR,DOR
      COMMON /G02/ CTIR(25),CTOR(25),CPIR(25),CPOR(25),TSR(25),TGR(25)
      COMMON /A03/ CSG
      COMMON /AI2/HRS,BR,WR,FL,NR
      COMMON /FI1/ PL
      COMMON /G01/ GGR,AWR,ATER,TGR1,DIRS,ATRS
      COMMON /G06/ JR
      COMMON /G03/ CTIRT,CPIRT,TGRT,JT,ZT,CBTP,TSRT
      COMMON /G04/ XSIRS,EPSRS,EPS2
      COMMON /AI3/ DI,CK,CAPI,CF
      COMMON /G05/ CTIRC,CPIRC,ZC,TGRC,XC,TSRC,ALEVC
      COMMON /G08/ XJC(25),HVC
      COMMON /GH/  HITP
      COMMON /GT6/ QT
C
      CMC=CM/3.
      GCC=GC/3.
      SGC =ROCL(CTIRT)/62.37364867
      APIC=(141.5/SGC)-131.5
      CKC =((CBT+460.)**(1./3.))/SGC
      CMW = ABS(CMWPF(APIC,CKC))
```

```
      CBTPF    = (CBTP - 273.) * 1.8 + 32.
      CMWI = ABS(CMWPF(CAPI,CK))
      HVC1      = HVPF (CMWI,CBT)
      HVC2      = HVPF (CMW,CTIRT)
      HVC=60.21
C
C   CALCULATION OF TEMPERATURE & PRESSURE
C
      ZO   = ZC - XSIRS
      TGRO = TGRC -5.* ZO
    2 TGAR     = (TGRO + TGRC) / 2.
      QGR      = WG* CPGI(TGRO,TGRC)
      CTIRF    = (CTIRC - 273.) * 1.8 + 32.
      HIC     = (CTIRC-298.)*(CPCG(CTIR(J))* XC+CPCL(CTIRC)*(1.-XC))
      XO = ( QGR/(6.*CMC))/HVC
      XCO=XO+XC
      CTORC= CTIRC +((  QGR / (6.* CMC) - XO * HVC) /
     &                  ((1.-XC)*CPCL(CTIRC)
     &                         +XC*CPCG(CTIRC)))
      CTBR     = (CTORC+ CTIRC) / 2.
      VCL      =  VCC(CTBR)
      CALL TPHTC(CTBR,CMW,XCO,TSRC,HVC,CMC,GCC,CPIRT)
      TSR(25) = CTBR +QGR/(6.* DIRS *TLR * 4.* ATAN(1.) * HITP)
      TSRCO=TSR(25)
      TFG=(TGAR-273.)*1.8+32.
      EF = -9.72222E-5*(TFG-2000.)+.458
      SUM=0.
      C(1)=0.
      DO 7 I=2,4
      C(I)=C(I-1)+WR/6.
      SUM=SUM+SFCFS(C(I))
   7  CONTINUE
      FAY      = EF * SUM/15.
      SIGMA=5.6696E-8*3600./4186.8
      GGCR   = WG * WGM * 2.2046226 / (BR*WR-6.*DOR*BR)
      RAD= SIGMA*(TF**4. -TSRCO**4.) * FAY
      TGRNC=2.*TSRCO-TGRC+(QGR/(3.*ATRS)-RAD)/
     &         HO(TGAR,TSRCO,GGR,DOR,AWR,ATER)
      FLAMEJ=RAD*ATRS
      ALEVO=ALEVC+FLAMEJ
      XCO=0.
      ALEVC=0.
      IF ( ABS(TGRNC - TGRO) .LE. EPSRS ) GO TO 3
      BINC=.01
      TGRO = TGRO+BINC*(TGRNC-TGRO)
      GO TO 2
   3  TGR(25)=TGRO
      TSR(25)=TSRCO
      CTIR(25)=CTIRC
      CTOR(25)=CTORC
      XJC(25)  =XO+XJC(24)
C
      RETURN
      END
```

```
C
C
C
C-----------------------------------------------------------------
C                 PPPPP  EEEEEE  K  K  V     V  A    L
C                 P   P  E       KKK    V   V  A A   L
C                 PPPPP  EEEEE   K  K    V V  AAAAA  L
C                 P      E       K   K    V  A     A LLLLL
C ----------------------------------------------------------------
C
C
C
      FUNCTION PEKVAL(V,API)
C
C  FINDS THE K FACTOR OF PETROLEUM FRACTION
C
C     INPUT: V(AT 122 F IN CENTISTOKES) , API
C
      A = -91.90768 * API + 9.14945 * API * API - 0.39620 * API ** 3. +
     &     0.00632 * API ** 4. + 347.56742
      B = 100.73420 * API -10.04215 * API * API + 0.43579 * API ** 3.-
     &     0.00697 * API ** 4. -369.64072
      PEKVAL = A * V ** 0.015 + B
C
      RETURN
      END
C
C
C
C-----------------------------------------------------------------------
C           H   H  SSSSS  TTTTT  EEEEE    A    M   M
C           H   H  S        T    E       A A   MM MM
C           HHHHH  SSSSS    T    EEEEE  AAAAA  M M M
C           H   H  SSSSS    T    EEEEE A     A M   M
C-----------------------------------------------------------------------
C
C
C
      FUNCTION HSTEAM (T,P)
C
C     INPUT: T , P
C
C     FINDS THE ENTHALPY OF STEAM ( KCAL/KG )
C
      TSF      = ( T - 273. ) * 1.8 + 32.
      PS       = P * 14.696
      A        = 0.00048 * PS + 0.46003
      B        = -0.35437 * PS + 1059.76347
      HSTEAM   = ( A * TSF + B ) * 2.2046226 * 0.25216
C
      RETURN
      END
```

APPENDIX E : DATA SET WHICH IS USED IN THE PROGRAM

DATA OF THE FURNACE PROGRAM

```
REFERENCE CONDITIONS: TEMPERATURE = 298.0 K
                      PRESSURE =  1.0 ATM


DATA OF AIR:          EXCESS AIR = 23.0 %
                      INLET TEMP. = 293.0 K


DATA OF FUEL OIL:     FLOW RATE=  32.3 LT/MIN
                      SULFUR MASS FRACTION = .0394
                      API GRAVITY = 11.40
                      VISCOSITY AT 122F = 2320. CS
                      INLET TEMP. = 407. K


DATA OF STEAM:        INLET TEMP. = 588.0 K
                      INLET PRESS.= 37.42 ATM


DATA OF FUEL GAS:     FLOW RATE = 316.9 M**3/HR
                      INLET TEMP .= 293.0 K
                      INLET PRESS.=  3.55 ATM
                      MOLE FRACTIONS OF    H2S =.009
                                           H2  =.460
                                           N2  =.064
                                           O2  =.004
                                           CO2 =.003
                                           CO  =.012
                                           C1  =.193
                                           C2  =.120
                                           C3  =.102
                                           IC4 =.0165
                                           NC4 =.0165
```

```
DATA OF FLUE GAS:     TEMP. AT THE OUTLET TO STACK = 725.0 K
                      TOTAL PRESSURE =  1.0 ATM
                      FLAME LENGTH =  6.562 FT.
                      AVERAGE LENGTH OF RADIANT BEAM = 14.8 FT.


DATA OF CHARGE:       UOP-K = 11.68
                      INLET TEMP. = 583.0 K
                      INLET PRESS. =  3.87 ATM
                      API  GRAVITY = 20.40
                      FLOW RATE = 7000. M**3/D
                      INLET TUBE DIAMETER = 0.5521 FT.
                      VISCOSITY = 7.3 CS  AT TEMPERATURE  372. K
                      VISCOSITY = 63.0 CS AT TEMPERATURE  323. K


DATA OF CONVECTION SECTION:
                      TUBE LENGTH = 19.96 M
                      INSIDE DIAMETER = 0.53 FT
                      OUTSIDE  DIAMETER = 0.55 FT
                      STAGGERING DISTANCE = 1.0 FT
                      # OF ROWS = 6
                      # OF TUBES / ROW = 4
                      TOTAL AREA = 268.96 FT**2
                      DIMENSIONS OF THE SECTION : WIDTH = 5.0 FT
                                                  LENGTH = 72.8 FT
                                                  HEIGHT = 10.6 FT


DATA OF RADIATION SECTION:
                      DIMENSIONS OF THE SECTION : WIDTH = 11.4 FT.
                                                  LENGTH = 70.8 FT
                                                  HEIGHT = 27.5 FT
                      TUBE NUMBER = 24
                      INSIDE DIAMETER = 0.69 FT.
                      OUTSIDE DIAMETER = 0.72 FT.
                      LENGTH = 19.96 M
                      TOTAL AREA = 126.8 FT**2
```

```
APPENDIX F : SAMPLE OUTPUT OF THE COMPUTER PROGRAM
==================================================

OUTPUT OF THE FURNACE PROGRAM
-----------------------------


CALCULATED INPUT VARIABLES OF CHARGE:
                       MASS FLOW                  =  1.358E5 Kg/hr
                       MASS FLOW RATE             =  1.251E6Lb/hr-ft**2
                       SPECIFIC GRAVITY                   = .932
                       CRITICAL TEMPERATURE               = 1095 F
                       BOILING TEMPERATURE AT 1 Atm       =  828 F



RESULTS OF MASS BALANCE:
                       MASS FLOW OF STEAM         =  586.5 Kg/hr
                       MOLAR FLOW OF AIR          =  1592 Kmole/hr
                       MOLAR FLOW OF FLUE GAS  = 1720.5 Kmole/hr
                       MOLECULAR WEIGHT OF FLUE GAS    =  28.6
                       MOLE FRACTION OF COMPONENTS OF FLUE GAS:
                                                          CO2 = .103
                                                          H2O = .126
                                                          SO2 = .002
                                                          O2  = .036
                                                          N2  = .733



RESULT OF ENERGY BALANCE : ADIABATIC FLAME TEMPERATURE = 1995 K



ESULTS OF CONVECTION SECTION :
                               WALL AREA = 1643.4 Ft**2
                               TOTAL EXCHANGE AREA = 8098.4 Ft**2
                               FLUE GAS MASS FLOW RATE = 1190 Lb/hr-ft**2

                       TEMPERATURE(K) DISTRIBUTION


 OF STAGE   CHARGE TEMPERATURE CHARGE OUTLET PRES.(ATM) FLUE GAS TEMPERATU
 --------   ------------------ ------------------------ -----------------

            INLET      OUTLET                           INLET    OUTLET

   1         583        585.1          3.514            725.0    750.8
   2         585.1      587.5          3.155            750.8    781.7
   3         587.5      590.6          2.796            781.7    819.0
   4         590.6      594.3          2.435            819.0    864.3
   5         594.3      598.9          2.073            864.3    919.8
   6         598.9      604.7          1.708            919.8    988.5
```

```
RESULTS OF RADIATION SECTION :
                           WALL AREA                  = 1477 Ft**2
                           TOTAL EXCHANGE AREA        = 8327 Ft**2
                           FLUE GAS MASS FLOW RATE = 134.5 Lb/hr-ft**2
```

TEMPERATURE(K) DISTRIBUTION

# OF STAGE	CHARGE INLET TEMP	CHARGE OUTLET TEMP	TUBE SURFACE TEMP	FLUE GAS CHARGE TEMP	OUTLET PRES	VAPOR FRACTION
1	604.7	612.0	632.8	1860.5	1.6	0.000
2	612.0	618.7	637.7	1802.6	1.4	0.000
3	618.7	624.9	642.3	1747.4	1.3	0.000
4	624.9	630.7	646.7	1694.8	1.1	0.000
5	630.7	636.0	650.3	1644.7	1.0	0.000
6	636.0	641.0	654.7	1596.8	0.8	0.000
7	641.0	645.7	658.4	1551.2	0.7	0.000
8	645.7	650.0	661.8	1507.6	0.5	0.000
9	650.0	654.1	665.1	1465.8	0.4	0.000
10	654.1	654.1	669.2	1425.9		0.056
11	654.1	654.1	654.1	1387.5		0.095
12	654.1	654.1	666.9	1350.5		0.139
13	654.1	654.1	666.1	1315.0		0.180
14	654.1	654.1	665.3	1280.6		0.220
15	654.1	654.1	664.7	1247.5		0.257
16	654.1	654.1	664.1	1215.5		0.293
17	654.1	654.1	663.5	1184.6		0.328
18	654.1	654.1	663.0	1154.6		0.361
19	654.1	654.1	662.5	1125.6		0.392
20	654.1	654.1	662.1	1097.4		0.422
21	654.1	654.1	661.7	1070.08		0.451
22	654.1	654.1	661.4	1043.4		0.479
23	654.1	654.1	661.0	1017.6		0.506
24	654.1	654.1	660.0	988.4		0.536

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