DEVELOPMENT OF A GENERALIZED APPROACH FOR THE THERMAL SIMULATION OF AN INDUSTRIAL HELICAL COIL TYPE THERMAL OIL HEATER

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ABSTRACT

The current study deals with the development of a mathematical model for the design and simulation of a thermal oil heater. A Thermal Oil Heater is a fired heater to produce hot thermal oil by firing desired fuel. A generalized approach is incorporated in the modeling for steady state Thermal Oil Heater design and simulation. Generalized model is developed for a typical double helical coil industrial Thermal Oil Heater. Heat transfer between flue gas and thermal oil is quite complex in this type of heat exchanger. A generalized heat exchanger network is developed to represent the heat interactions between thermal oil and flue gas. This network is used for the development of a mathematical model and an iterative technique for the solution of mathematical model is employed. The mathematical model is used for the simulation of experimental thermal oil heater and validated with the experimental result. The mathematical model is further employed to study the effect of various design and operating parameters on the performance of thermal oil heater. This study can be used for the design and optimization of thermal oil heater.

Keywords: Thermal Oil Heater, Thermic Fluid Heater, convective passes, temperature profile, helical coiled tubes, mathematical modeling.

1. INTRODUCTION

Thermal Oil Heater or Thermic Fluid Heater is basically a heat exchanger, where thermal oil or thermic fluid is heated by using hot flue gas. Thermal Oil Heaters are widely used for indirect process heating. These heaters employ thermal oil (or thermic fluid) (petroleum based organic compounds with boiling point of approx. 850 K) as the heat transfer medium. The Thermal Oil Heater incorporates a closed loop system for its operation, thus achieving higher system efficiency and temperatures at moderate pressures [1].

The system under consideration is a liquid fuel fired Thermal Oil Heater. The system comprises of a central combustion chamber and surrounding concentric double helical coil. The system comprises of an outer jacket concentric to the helical coils. The thermal oil passes through the helical coils (spiral flow) and acts as a heat sink. The flue gases generated in the central portion of Thermal Oil Heater (denoted as the radiation heat transfer section) via the combustion of the liquid fuel pass through the annular passage between the concentric helical coils (denoted as the first convective pass) and the passage between the outer helical coil and the outer jacket (denoted as the second convective pass). Fig. 1 shows a simplified layout showing the flue gas and thermal oil flow of the Thermal Oil Heater.

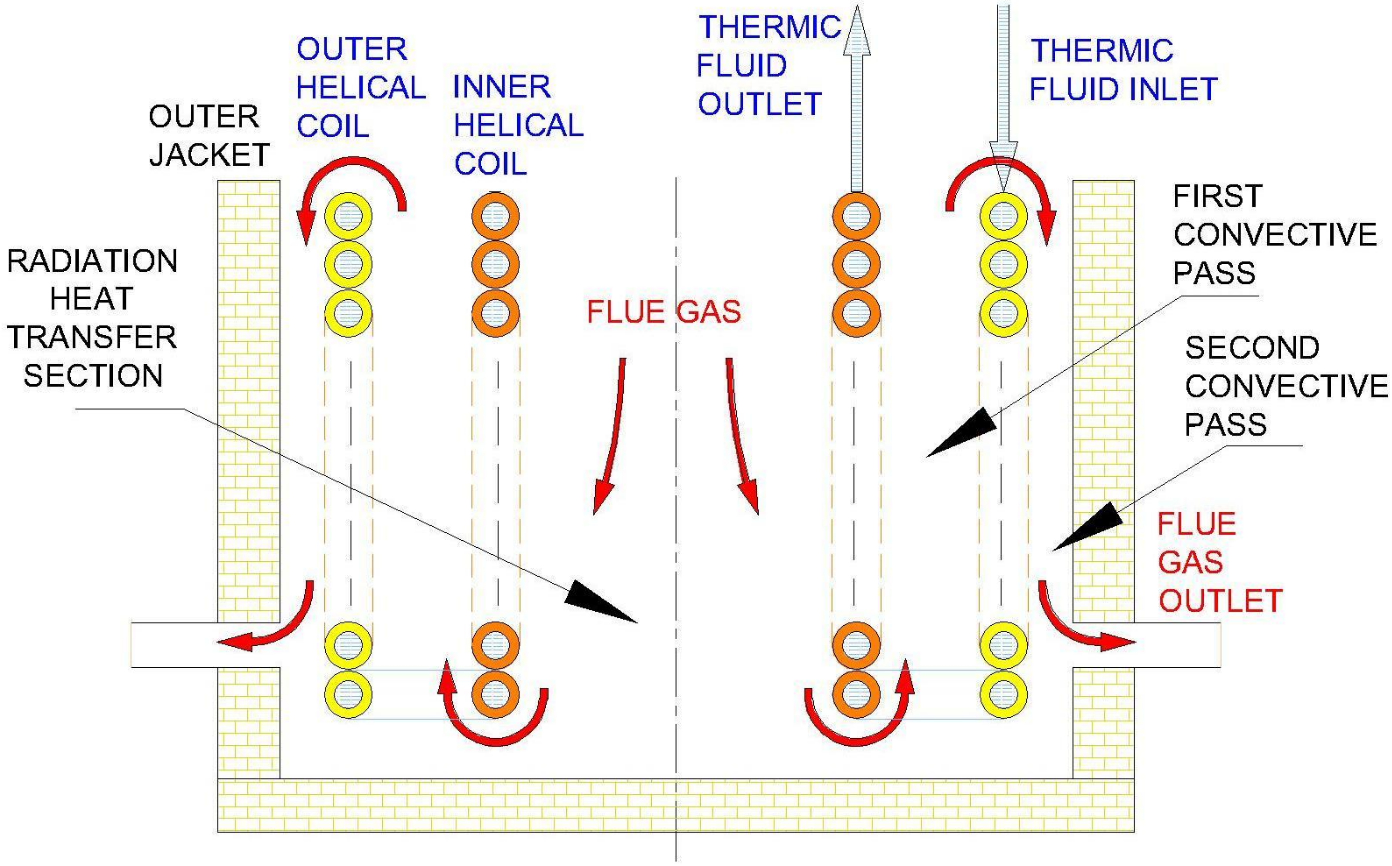
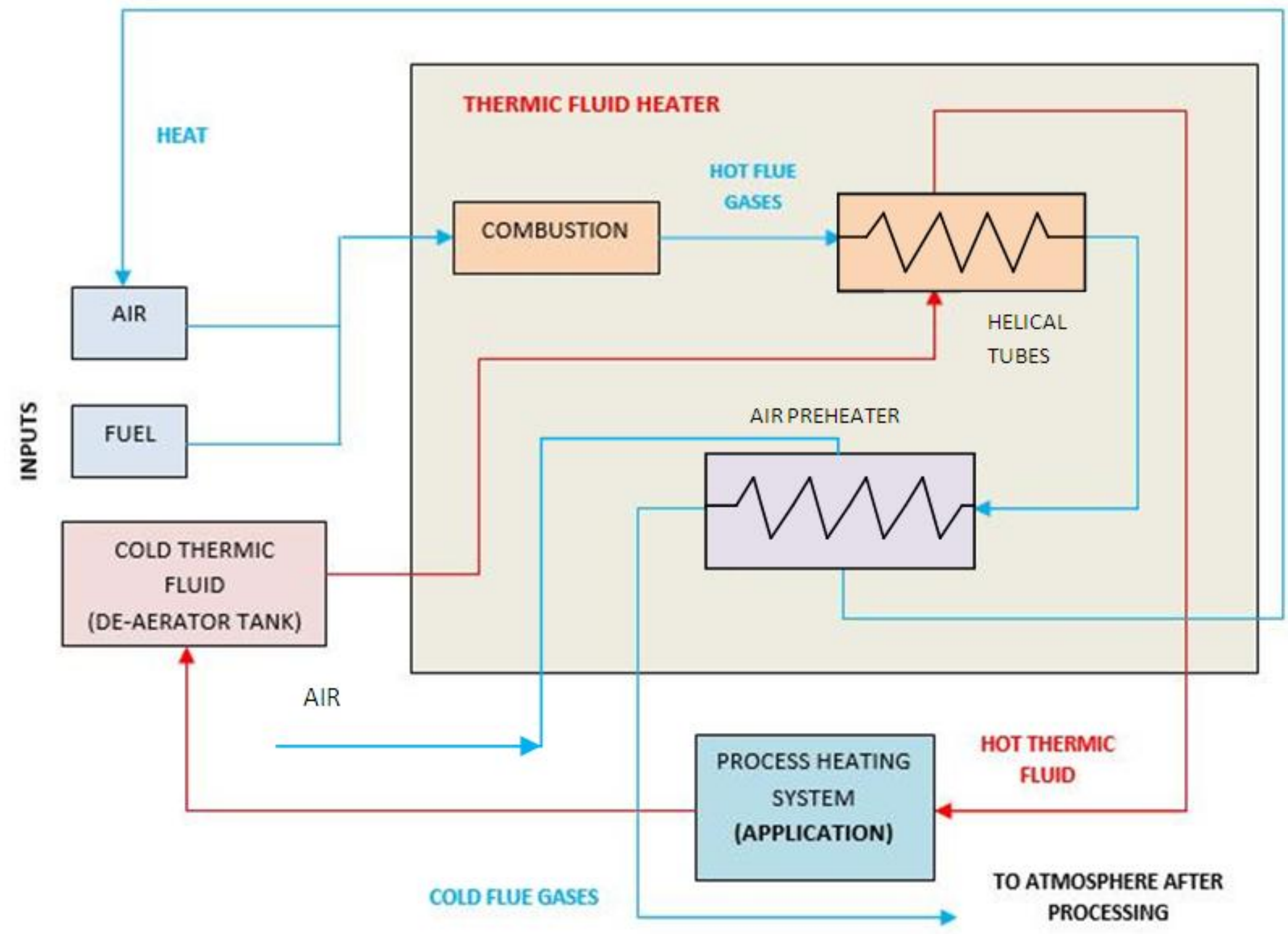


Fig. 1: Simplified configuration of Thermal Oil Heater

The combustion of fuel in the presence of air produces flue gas at high temperature. The energy transfer takes place via heat exchange between the flue gas and the thermal oil to produce hot thermal oil. The hot thermal oil rejects heat to the process fluid in a process heat exchanger and the relatively cold thermal oil enters to the helical coils of a thermal oil heater. The temperature of the thermal oil rises after receiving heat from the flue gases, whereas the temperature of the flue gas drops. In this way, the temperature of the thermal oil is raised to the required temperature at the desired fluid flow rate. The high temperature of the exit flue gas is used for air preheating. The detailed interaction of air, fuel, flue gas & thermal oil is shown in Fig. 2 in the form of a block diagram.



Index:

Flue Gas circuit

Thermal Oil circuit

Fig. 2: Detailed working circuit of Thermal Oil Heater

2. CHALLENGES IN THERMAL DESIGN OF THERMAL OIL HEATER

Design and simulation of a Thermal Oil Heater requires the development of a mathematical model to predict the temperature profiles and heat transfer rates accurately at various sections at different load requirement.

The heat exchange between the flue gas and the thermal oil is quite complex. The flue gas passes through the different section of thermal oil heater transferring heat to the thermal oil. The flue gases flowing through the core of the heater rejects heat to the inner walls of the inner helical coil, as shown in Fig. 1. Radiation is the predominant mode of heat transfer in this section because of high flame temperature. This heat is received by the thermal oil flowing through the inner helical coil tubes.

The flue gases flowing through the annular passage between the inner and outer helical coils reject heat to the outer walls of the inner helical coil and inner walls of the outer helical coil. Similarly, the flue gases flowing through the annular passage between the outer helical coil and the outer jacket reject heat to the outer wall of the outer helical coil and the inner wall of the outer jacket in the case of jacketed air preheating. The heat exchange in these sections takes place mainly through convection. Heat transfer between flue gas & thermal oil is extremely complicated as the inner coil receives the heat from the flue gas passing through the central section of thermal oil heater through radiation and from the flue gas passing through the annular section between inner and outer coil through convection. Outer coil receives the heat from flue gas passing through the annular section between two coils and also from the flue gas passing between outer coil and jacket. In the same manner, flue gas passing through the annular section between two coils reject heat to both inner and outer coil.

The resultant flue gas and thermal oil temperature profile is extremely complicated and these temperatures are dependent on each other. Hence, a different approach is needed to represent the complex heat transfer interaction between the flue gas and thermal oil and the resultant temperatures at the aforementioned sections.

This requires selection of appropriate radiation and convective heat transfer model. The selection of appropriate correlation for convective heat transfer analysis is especially important due to its unconventional flow profile, which cannot be approximated as annular flow or flow over the tube bank. A study has been done by Kharat et.al [2] which deals with developing a correlation for heat transfer coefficient for flow between concentric helical coils. The correlations yield accurate results in the analysis of heat transfer for the flow between two helical coils. The gap between the inner and outer helical coil (denoted as gap ratio), the tube diameter and tube thickness are found to be crucial parameters for the heat transfer performance of a helical coil heat exchanger.

A study carried out by Hottel et al [3] deals with heat transfer calculations for the furnace, which can be used for the radiation heat transfer analysis of the central section of the heat exchangers. The study approximates the entire volume of flue gas to be at the same temperature, such that the flue gas mixture in the combustion chamber is stirred. The heat transfer model is known as 'Hottel's well stirred reactor model' [3]. Hottel [4] also presents the correlations for calculating emissivity of gases and gas mixtures. Graphical data has been provided for emissivity as a function of gas temperature for CO_2 and H_2O [5].

3. METHODOLOGY

The thermal simulation of the Thermal Oil Heater is carried out by mathematical modeling of the individual sections of the heater (refer Fig. 1). These models are then coupled with each other to provide the integrated mathematical model to represent the thermal interaction of different section of the Thermal Oil Heater. This mathematical model represents the heat transfer in the various sections of thermal oil heater and the energy balance equations for the flue gas and thermal oil. Iterative computation techniques were employed for obtaining the results. These results were compared against the data obtained from experimental analysis of the Thermal Oil Heater in order to validate the accuracy of the mathematical model. Computer programming for modeling and simulation is carried out using 'Visual Basic 6'.

3.1 Temperature profiles in the Thermal Oil Heater system

The flow pattern of the thermal oil and the flue gas is shown in Fig. 1 and described in Section 1.2. The temperature profile is shown in Fig. 3 and explained in detail below.

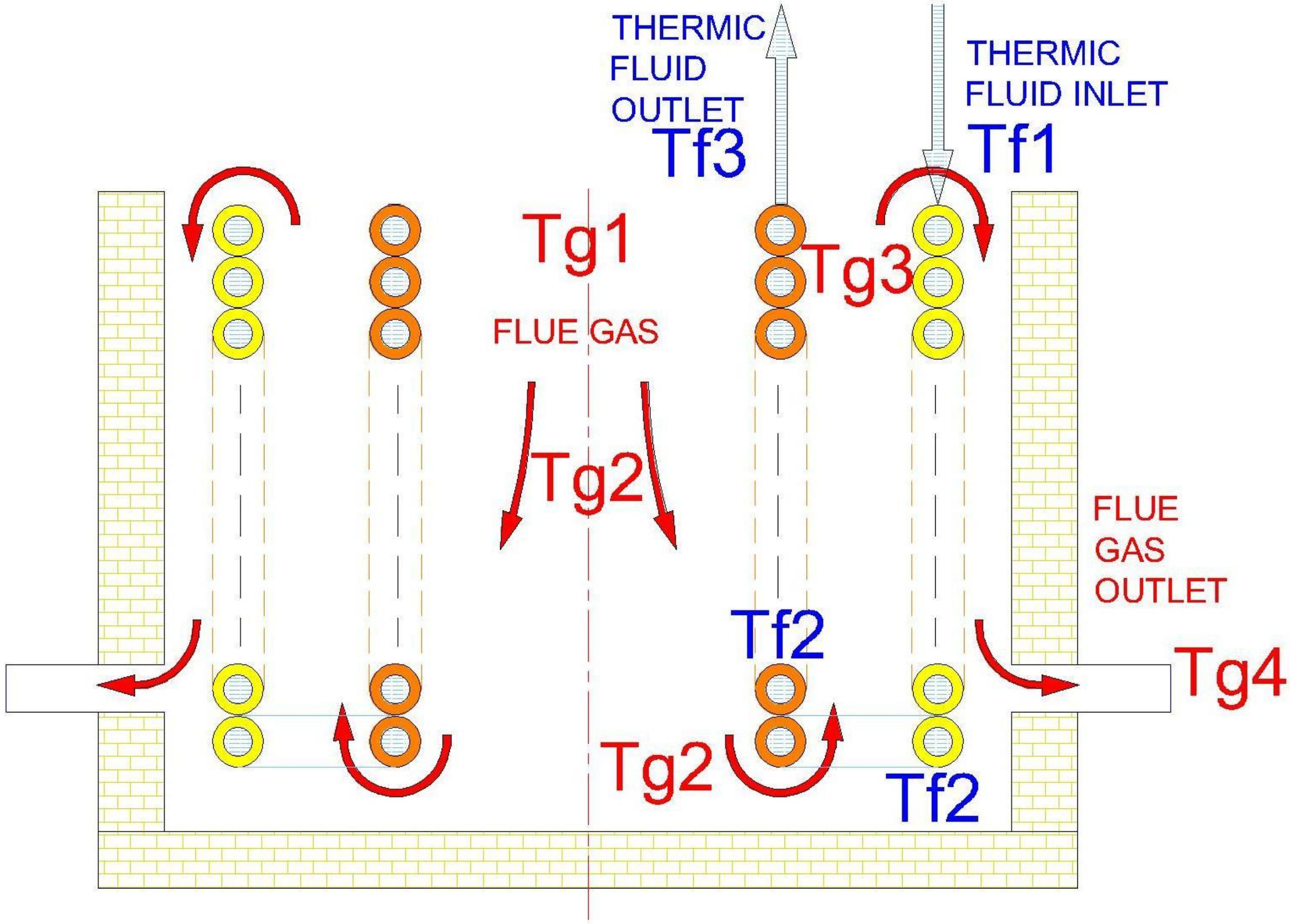


Fig 3: Temperature profiles for flue gases and thermal oil

Let,
The central section of the heater be denoted as Section I (Combustion section),
The section of the heater between the helical coils be section II (First convective pass section),
The section of the heater between the outer helical coil and the outer wall be section III (Second convective pass section or section C).

Flue gas outlet temperature in the section I (furnace) is T_{g2}. The temperature of the flue gas varies from T_{g2} to T_{g3} in section II and varies from T_{g3} to T_{g4} in section III. Similarly the temperature of the thermal oil varies from T_{f1} to T_{f2} in the outer coil and from T_{f2} to T_{f3} in the inner coils.

3.2 Heat transfers and Energy balance in the system

The heat transfer taking place via various sections of the Thermal Oil Heater is shown in Fig. 4.

From the 1st law of thermodynamics:

$$Q_{gen} = Q + Q_{rej} \qquad \text{... (1)}$$

Where,

Q_{gen} = Net heat generation (kW)
Q = Net heat transfer (kW)
Q_{rej} = Heat rejection to stack (kW)
The heat is transferred to the thermal oil via the helical coils in the radiation section and the convective sections.

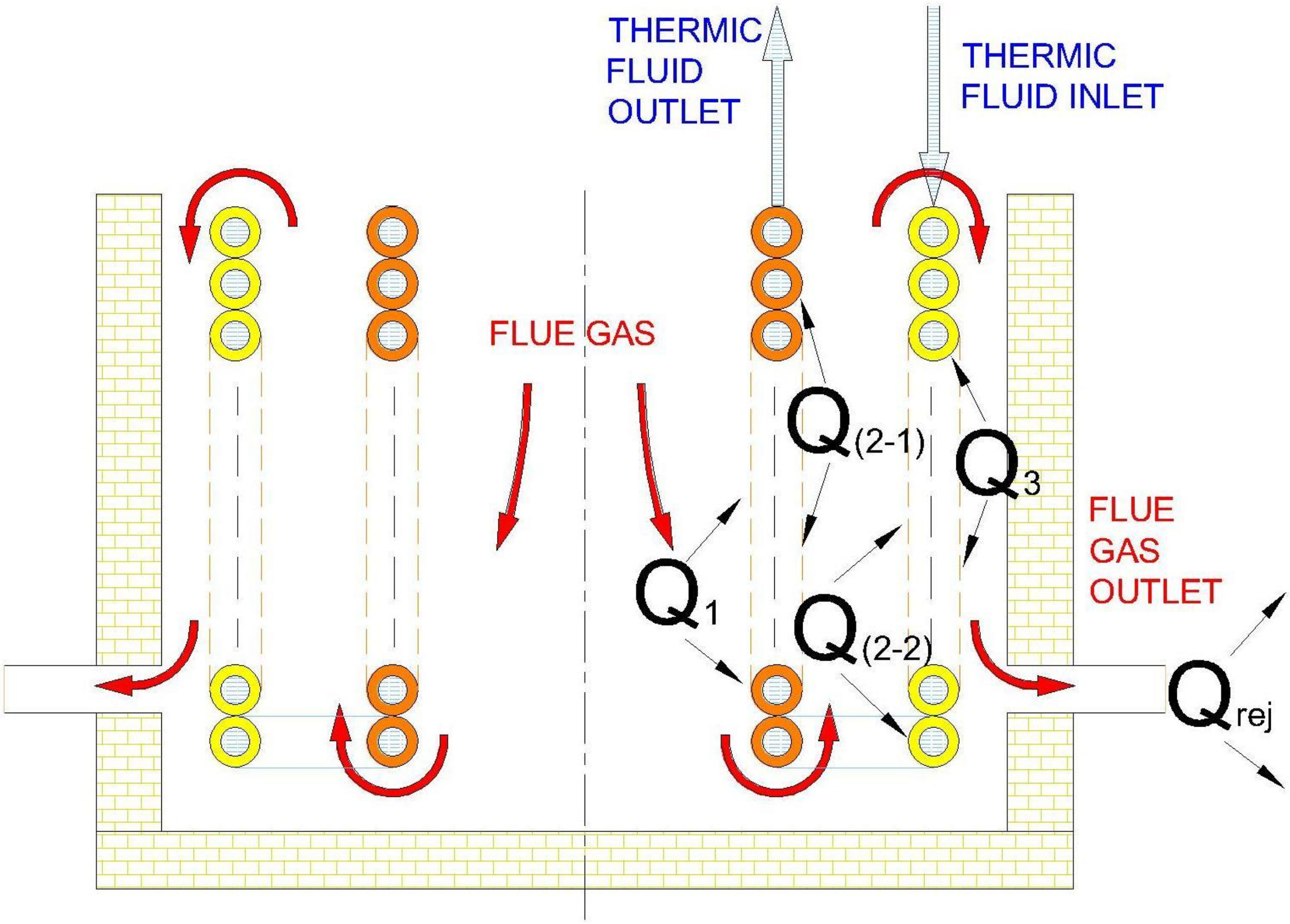


Fig. 4: Heat transfer at all sections in Thermal Oil Heater

Flue gas heat is transferred to the thermal oil in the central section with radiation as a dominant mode of heat transfer, between the two helical coils and between outer helical coil and jacket with convection as dominant mode of heat transfer. Net heat transfer from the flue gas to thermal oil can be expressed by the following equation.

$$Q = Q_1 + Q_2 + Q_3 \qquad \ldots (2)$$

Q_1, Q_2 and Q_3 represent the heat transfer in first, second and third pass of the thermal oil heater.

Flue gas heat in the first pass is transferred to the inner coil & flue gas in the third pass is transferred to the outer coil. Flue gas in the second pass is distributed between inner & outer coil. Following equation represent the distribution second pass heat transfer between inner and outer coil.

$$Q_2 = Q_{2-1} + Q_{2-2} \qquad \ldots (3)$$

Where,

Q_{2-1} = Second pass flue gas heat transfer to the inner coil (kW)

Q_{2-2} = Second pass flue gas heat transfer to the outer coil (kW)

3.3 Furnace Analysis

The combustion analysis is carried out to determine the flue gas composition, the stoichiometric air-fuel ratio and air quantity as well as flue gas quantity with the predefined excess air.

A mathematical model is developed for the radiation analysis for accurate prediction of the temperatures and heat transfers in the central section of thermal oil heater. The combustion of the fuel takes place in this section of the Thermal Oil Heater. The temperature of the flue gases in this section is of the order of 1000 K. At this high temperature, radiation dominates the heat transfer between flue gases and Thermal oil. Hottel's well stirred furnace model is used in this section, where uniform temperature throughout the furnace is assumed neglecting any temperature gradient in the furnace [3] [6].

It is required to calculate the emissivity of the flue gas mixture in order to calculate the heat transfer and temperature profile. The emissivity of gas depends on the flue gas temperature, soot concentration and the partial pressure of absorbing gas [5].

Emissivity of the flue gas mixture is function of mean beam length, flue gas temperature and partial pressure of carbon dioxide & water vapor. Emissivity of flue gas is calculated by the following equations.

$$\epsilon_g = \mathrm{b} \times [1 - e^{(-K_e \times L_b)}] \qquad \text{... (4)}$$

Where,

b= Gray gas emissivity in energy fraction of black body spectrum

K_e = Absorption coefficient of gray gas

L_b= Mean beam length (m)

Absorption coefficient of the flue gas is the function of flue gas temperature and the partial pressure of the absorbing gases like water vapor and carbon dioxide. This is calculated by using following equation.

$$K_e = \frac{\{[0.8 + 1.6 \times X_w][1 - (0.38 \times \frac{T_{g2}}{1000})][X_w + X_c]\}}{\sqrt{(X_w + X_c \times L_b)}} \qquad \text{... (5)}$$

Where,

T_{g2}= Flue gas outlet temperature (K)

X_w = Partial pressure of water vapor

X_c= Partial pressure of carbon dioxide

Heat transfer (Q_1) taking place due to radiation [2] is calculated by using following equation.

$$Q_1 = \frac{A_{rad} \times \sigma \times ({T_{g2}}^4 - {T_{t1}}^4)}{(\frac{1}{\epsilon_{t1}} + \frac{1}{\epsilon_{g2}} - 1)} \qquad \text{... (6)}$$

Where,

A_{rad}= Projected heat transfer area (m^2)

σ = Stefan Boltzmann constant

T_{t1}= Tube wall temperature (K)

ϵ_{t1}= Emissivity of tube metallic surface

ϵ_{g2}= Flue gas emissivity

Following equation represents the energy balance in the furnace and can be used for the calculation of flue gas temperature at the outlet of the furnace.

$$M \times CV = Q_1 + m_g \times c_{pg1} \times (T_{g2} - T_{g1}) \qquad \text{... (7)}$$

M= Rate of combustion (kg/s)

CV= Calorific value of fuel (kJ/kg)

m_g= Mass flow rate of Flue gas (kg/s)

c_{pg1}= Specific heat of flue gas in Section I (kJ/kg-K)

T_{g1}= Flue gas inlet temperature (K)

3.5 Mathematical Modeling for the Convective Sections

After the radiation heat transfer in the furnace, relatively cold flue gas passes through the annular space between two coils before passing through another annular space between outer helical coil and jacket. In these two passes of the flue gas, dominant mode of the heat transfer is convection. These passes are referred as first convective pass and second convective pass. These convective sections are extremely crucial in the design, since 50-60% of the total heat transfer through the system takes place in the convective sections.

Calculation of heat transfer in these sections is extremely challenging due to unconventional flow passage. Kharat et al. [2] present the modified correlation for the estimation of heat transfer coefficient for flow between two helical coils. This investigation suggests that the heat transfer coefficient is also dependent on the gap ratio of coils. The gap ratio of coil can be defined as:

$$G_{ratio} = (D_o - D_i)/d \qquad \text{... (8)}$$

Where,

D_o= Pitch circle diameter of outer coil (m)

D_i= Pitch circle diameter of inner coil (m)

d= Outer diameter of tube (m)

A modified equation for Nusselt number calculation is given as [2]:

$$Nu = 0.02652 \times Re^{0.8347} \times \ Pr^{0.3} \times G_{ratio}{}^{0.09686} \qquad \text{... (9)}$$

The nature of equation is similar to the Nusselt number equation for annular gap and modified by an additional factor dependent on gap ratio.

The Nusselt number for flue gas domain can thus be calculated from the above equations and is used for the calculation of gas side heat transfer coefficient by using following equation.

$$h_g = Nu \times K/D \qquad \text{... (10)}$$

Thermal oil side heat transfer coefficient (h_f) is calculated by using Dittus-Boelter equation [5]. Overall heat transfer coefficient for heat transfer tube is calculated using inside heat transfer coefficient (h_f), outside heat transfer coefficient (h_g) and thermal conductivity of the tube wall.

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3.6 Heat transfer calculation

Q_1, Q_2 & Q_3 are the heat transfer in the various section of the boiler. Q_1 is the radiation heat transfer and calculated by using Eqn. (4). Q_2 is the net heat transfer in the second pass of the thermal oil heater and distributed to inner and outer coil. Q_{2-1} & Q_{2-2} are the second pass heat transfers to the inner and outer coil. Second pass heat transfer to the inner coil (Q_{2-1}) can be calculated as follows.

$$Q_{2-1} = \frac{U_{2-1} \ \times A_{2-1} \times [(T_{g2} \ - \ T_{f2}) - (T_{g3} \ - \ T_{f3})]}{ln\,\{(T_{g2} \ - \ T_{f2})/(T_{g3} \ - \ T_{f3})\}} \qquad \text{... (11)}$$

Where,

$U_{2-1} =$ Overall heat transfer coefficient on the thermal oil side for the first convective pass heat transfer to the outer face of the inner helical coil (W/m^2-K)

$T_{g2} =$ Temperature of flue gases after the heat transfer process in central section (K)

$T_{g3} =$ Temperature of flue gases after the heat transfer process in first convective pass (K)

$T_{f2} =$ Inner coil inlet thermal oil temperature (K)

$T_{f3} =$ Inner coil outlet thermal oil temperature (K)

Log mean temperature difference is calculated with parallel flow consideration for the calculation of $Q_{2-1,}$ as flue gas and thermal oil flow in the same direction. For the calculation of Q_{2-2}, log mean temperature difference is calculated with counter flow consideration due to change in direction of thermal oil flow. Second pass heat transfer to the outer coil (Q_{2-2}) can be calculated as follows.

$$Q_{2-2} = \frac{U_{2-2} \times A_{2-2} \times [(T_{g2} - T_{f2}) - (T_{g3} - T_{f1})]}{ln\,\{(T_{g2} - T_{f2})/(T_{g3} - T_{f1})\}} \qquad \text{... (12)}$$

Where,

$U_{2-2} =$ Overall heat transfer coefficient on the thermal oil side for the first convective pass heat transfer to the inner face of the outer helical coil (W/m^2-K)

$T_{f1} =$ Inlet temperature of thermal oil (K)

For the calculation of heat transfer in third pass, log mean temperature difference is calculated with the consideration of parallel flow due to change in the direction of flue gas flow. Q3 is the third pass heat transfer to the outer coil and calculated as follows.

$$Q_3 = \frac{U_3 \times A_3 \times [(T_{g3} - T_{f1}) - (T_{g4} - T_{f2})]}{ln\,\{(T_{g3} - T_{f1})/(T_{g4} - T_{f2})\}} \qquad \text{... (13)}$$

$U_3 =$ Overall heat transfer coefficient on the thermal oil side for the first convective pass heat transfer to the outer face of the outer helical coil (W/m^2-K)

$T_{g4} =$ Temperature of the flue gas at the outlet (K)

Q1 & Q2-1 are het transfer to thermal oil passing through the inner coil. Energy balance equation for the thermal oil passing through the inner coil is expressed as follows.

$$Q_1 + Q_{2-1} = m_f \times c_{pf1} \times (T_{f3} - T_{f2}) \qquad \text{... (14)}$$

$m_f =$ Average mass flow rate of thermal oil in the inner coil (kg/s)

$c_{pf1} =$ Specific heat of thermal oil at a constant pressure in the inner coil (kJ/kg-K)

Q_{2-2} & Q_3 are heat transfers to thermal oil passing through the outer coil. Energy balance equation for the thermal oil passing through the outer coil is expressed as follows.

$$Q_{2-2} + Q_3 = m_f \times c_{pf2} \times (T_{f2} - T_{f1}) \qquad \text{... (15)}$$

$c_{pf2} =$ Specific heat of thermal oil at a constant pressure in the outer coil (kJ/kg-K)

In the same manner, energy balance equation for the flue gas can be written. Equation (8) shows the energy balance of the in the furnace section of the Thermal Oil Heater. Following equations represent energy balance of flue gas in second and third pass of thermal oil heater.

$$Q_2 = m_g \times c_{pg2} \times (T_{g2} - T_{g1}) \qquad \text{... (16)}$$

$$Q_3 = m_g \times c_{pg3} \times (T_{g3} - T_{g2}) \qquad \text{... (17)}$$

$c_{pg2} =$ Specific heat of flue gas in Section II (kJ/kg-K)

$c_{pg3} =$ Specific heat of flue gas in Section III (kJ/kg-K)

These equations represent change in temperature of the flue gas in second & third pass of the thermal oil heater.

4. THE SYSTEM OF EQUATIONS AND SOLUTION TECHNIQUE

These energy balance equations and heat transfer equations are combined to generate a simplified system of equation to represent interdependency of thermal oil and flue gas temperature in different sections of thermal oil heater.

$$f_1 = \frac{[A_{rad} \times \sigma \times (T_{g2}{}^4 - T_{t1}{}^4)]}{[1/\epsilon_{t1} + 1/\epsilon_g - 1]} - (M \times CV) + [m_g \times c_{pg2} \times (T_{g2} - T_{g1})] = 0 \qquad \text{... (18)}$$

$$f_2 = \frac{U_{2-1} \times A_{2-1}\left[\left(T_{g2}-T_{f2}\right)-\left(T_{g3}-T_{f3}\right)\right]}{ln\left\{\left(T_{g2}-T_{f2}\right)/\left(T_{g3}-T_{f3}\right)\right\}} + \frac{U_{2-2} \times A_{2-2}\left[\left(T_{g2}-T_{f2}\right)-\left(T_{g3}-T_{f1}\right)\right]}{ln\left\{\left(T_{g2}-T_{f2}\right)/\left(T_{g3}-T_{f1}\right)\right\}} - \left[m_g \times c_{pg2} \times \left(T_{g2}-T_{g1}\right)\right] = 0 \quad ...(19)$$

$$f_3 = \frac{U_3 \times A_3 \times \left[\left(T_{g3}-T_{f1}\right)-\left(T_{g4}-T_{f2}\right)\right]}{ln\left\{\left(T_{g3}-T_{f1}\right)/\left(T_{g4}-T_{f2}\right)\right\}} - \left[m_g \times c_{pg2} \times \left(T_{g2}-T_{g1}\right)\right] = 0 \quad ...(20)$$

$$f_4 = \frac{\left[A_{rad} \times \sigma \times \left({T_{g2}}^4 - {T_{t1}}^4\right)\right]}{\left[1/\epsilon_{t1} + 1/\epsilon_g - 1\right]} + \frac{U_{2-1} \times A_{2-1}\left[\left(T_{g2}-T_{f2}\right)-\left(T_{g3}-T_{f3}\right)\right]}{ln\left\{\left(T_{g2}-T_{f2}\right)/\left(T_{g3}-T_{f3}\right)\right\}} - m_f \times c_{pf3} \times \left(T_{f3}-T_{f2}\right) = 0 \quad ...(21)$$

$$f_5 = \left[m_g \times c_{pg} \times \left(T_{g2}-T_{g1}\right)\right] + \frac{U_{2-2} \times A_{2-2}\left[\left(T_{g2}-T_{f2}\right)-\left(T_{g3}-T_{f1}\right)\right]}{ln\left\{\left(T_{g2}-T_{f2}\right)/\left(T_{g3}-T_{f1}\right)\right\}} - m_f \times c_{pf2} \times \left(T_{f2}-T_{f1}\right) = 0 \quad ...(22)$$

These equations represent a system of five non-linear independent equations with five primary variables, viz. T_{g2}, T_{g3}, T_{g4}, T_{f2}, and T_{f3}. These five equations are written as different functions f_1, f_2, f_3, f_4 and f_5.These are solved by using Newton Raphson technique for desired accuracy.

The solution to the equations is computed using the iterative Newton-Raphson method applied to multiple variables, given by the following equation [7].

$$\{T_{new}\} = \{T_{old}\} - \xi \times [\,J\,]^{-1} \times \{f\} \quad ...(23)$$

The above equation allows iterative computation of the temperatures, by accounting for a change in the temperature values over the previous iteration step (initial guess values for the first iteration). The T_{new} vector gives the refined values of temperatures from the T_{old} vector.

$$\begin{bmatrix} T_{g2} \\ T_{g3} \\ T_{g4} \\ T_{f2} \\ T_{f3} \end{bmatrix}_{New} = \begin{bmatrix} T_{g2} \\ T_{g3} \\ T_{g4} \\ T_{f2} \\ T_{f3} \end{bmatrix}_{Old} - \xi \times \begin{bmatrix} \frac{\partial f_1}{\partial T_{g2}} & \frac{\partial f_1}{\partial T_{g3}} & \frac{\partial f_1}{\partial T_{g4}} & \frac{\partial f_1}{\partial T_{f2}} & \frac{\partial f_1}{\partial T_{f3}} \\ \frac{\partial f_2}{\partial T_{g2}} & \frac{\partial f_2}{\partial T_{g3}} & \frac{\partial f_2}{\partial T_{g4}} & \frac{\partial f_2}{\partial T_{f2}} & \frac{\partial f_2}{\partial T_{f3}} \\ \frac{\partial f_3}{\partial T_{g2}} & \frac{\partial f_3}{\partial T_{g3}} & \frac{\partial f_3}{\partial T_{g4}} & \frac{\partial f_3}{\partial T_{f2}} & \frac{\partial f_3}{\partial T_{f3}} \\ \frac{\partial f_4}{\partial T_{g2}} & \frac{\partial f_4}{\partial T_{g3}} & \frac{\partial f_4}{\partial T_{g4}} & \frac{\partial f_4}{\partial T_{f2}} & \frac{\partial f_4}{\partial T_{f3}} \\ \frac{\partial f_5}{\partial T_{g2}} & \frac{\partial f_5}{\partial T_{g3}} & \frac{\partial f_5}{\partial T_{g4}} & \frac{\partial f_5}{\partial T_{f2}} & \frac{\partial f_5}{\partial T_{f3}} \end{bmatrix}^{-1} \times \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \end{bmatrix}_{Old} \quad ...(24)$$

Here,

ξ = Under-damping factor to ensure that the solution does not diverge while iterating.

The Jacobian [J] is a 5 x 5 matrix which is generated by using numerical differentiation of each functions (f_1, f_2, f_3, f_4 and f_5) w.r.t five variables (T_{g2}, T_{g3}, T_{g4}, T_{f2}, and T_{f3}).

7. CASE STUDY: VALIDATION OF MATHEMATICAL MODEL RESULTS WITH EXPERIMENTAL RESULTS

The generalized simulation model is applied for the test model of Thermal Oil Heater (Thermax Ltd.) for the validation. Thermal oil geometry has been shown in Fig. 5 & Table 1.

Table 1: Dimensions of the liquid fuel Thermal oil heater

Parameter	Inner Coil	Outer Coil
Pitch Circle Diameter	1263.5 mm	1466.5 mm
Tube Nominal Diameter	63.5 mm	63.5 mm
Tube thickness	3.4 mm	3.4 mm
Number of starts	4	4
Number of turns	45	47

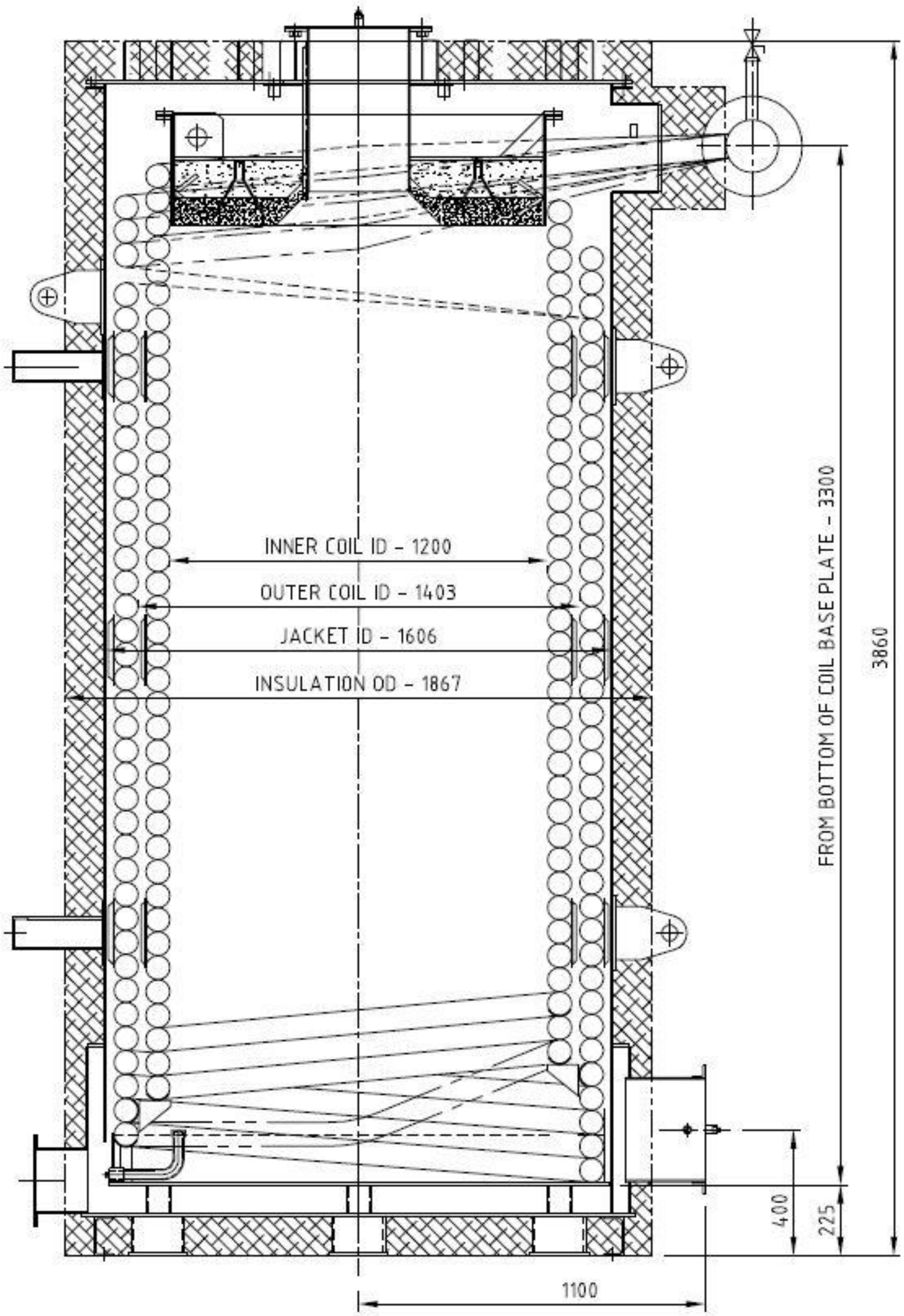

Fig 5: Cut section front view of Thermal Oil Heater Model TPDi-15/10

Table-2 lists input parameter and the result of simulation as output parameter.

Table 2: Steady state Thermal simulation inputs and results

Parameter		Value
Input Values	CV	9650 kCal/kg
	M	180 kg/hr
	m_f	90 m^3/hr
	T_{g1}	305.00 K
	Excess air percentage	20
Output Values	T_{g2}	1515.67 K
	T_{g3}	702.03 K
	T_{g4}	628.56 K
	T_{f1}	520.00 K
	T_{f2}	531.68 K
	T_{f3}	552.71 K
	Q_{rad}	690138.12 W
	Q_2	889461.08 W
	Q_3	78590.60 W
	Q_{rej}	361611.99 W
	Thermal Efficiency	82.09 %

7.1 Validation of results:

Table 2 shows the result of simulation for full load condition and the result is compared with experimental result for the validation of the model. Simulation is carried with different load condition by changing the fuel firing rate. Fig.6 shows the variation of thermal oil outlet temperature as a function of fuel firing rate and its comparison with experimental result. Similar analysis has been conducted for flue gas outlet temperature and plotted in Fig. 7. This shows the maximum error of 4.37 % well within acceptable limit.

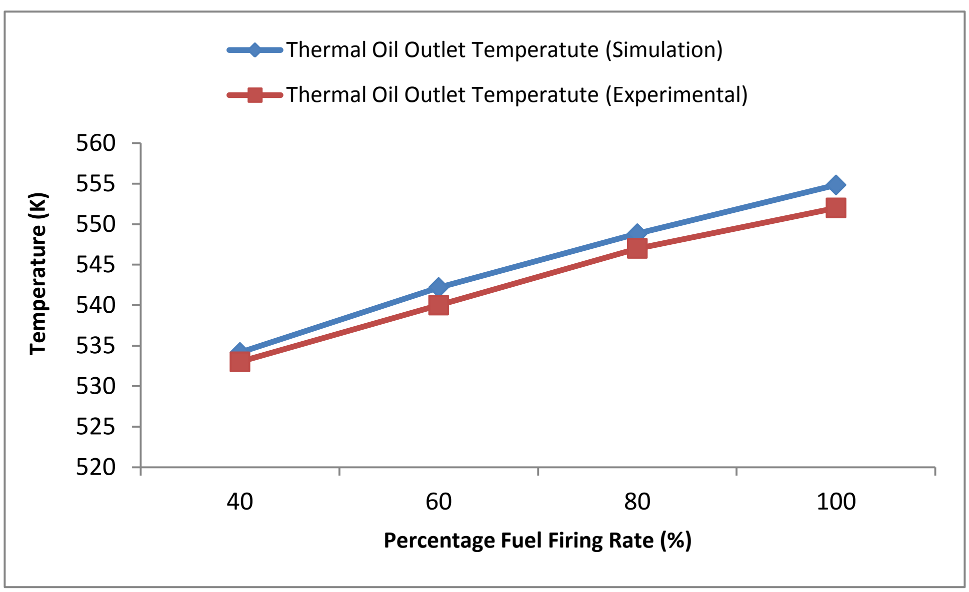

Fig. 6: Experimental and mathematical model for thermal oil temperature.

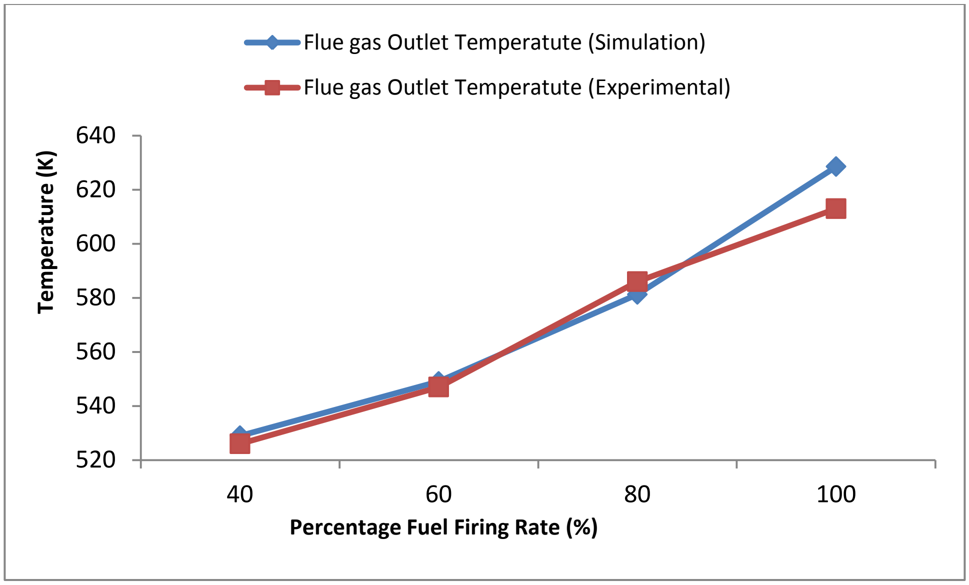

Fig. 7: Experimental and mathematical model for flue gas temperature

8. RESULTS & DISCUSSION

Performance of thermal oil heater is simulated in different operating environment by changing the input variables. The effect of these variables on boiler performance is studied.

8.1 Effects of firing rate on thermal oil heater performance.

Thermal oil heater is simulated at different firing rate and the result is plotted in Fig. 8. This shows the effect of firing rate on the flue gas temperature and thermal oil temperature. Flue gas temperature increases with increase in fuel firing rate. Both flue gas quantity and heat transfer coefficient increase with increase in fuel firing rate but the flue gas quantity increases with higher exponent. This leads to the higher flue gas temperature. As the total heat transfer increases with the increase in fuel firing rate, the thermal oil temperature rise and outlet temperature increase with increase in fuel firing rate.

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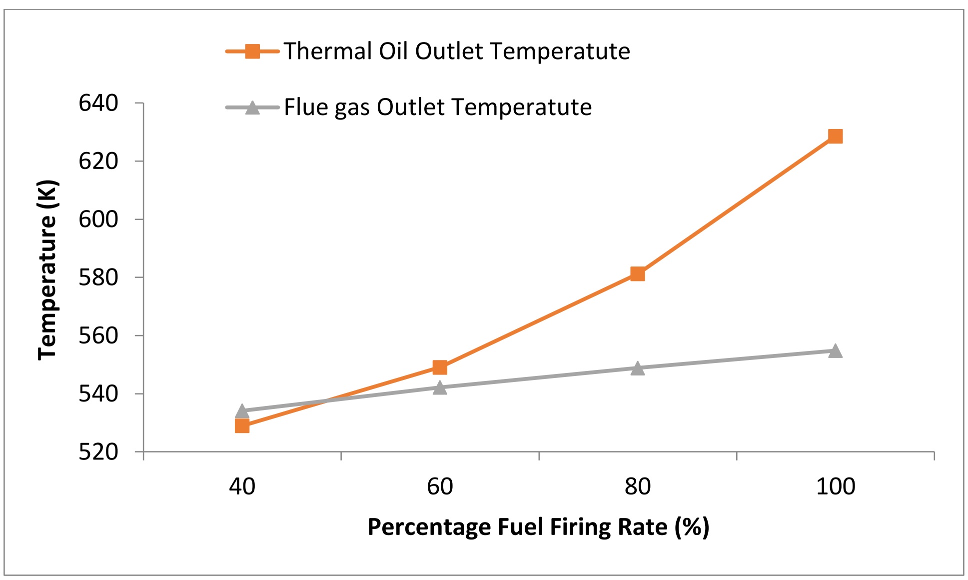

Fig. 8: Thermal oil and Flue Gas Outlet Temperature v/s Firing Rate

Heat transfer in the various section of thermal oil heater increases with increase in fuel firing rate. The effect of fuel firing rate on the performance of thermal oil heater is plotted in Fig. 9. Fig. 9 shows the heat transfer rate in the different section of thermal oil heater. The increase in heat transfer with increase in firing rate can be attributed to increase in heat transfer coefficient & mean temperature difference. This also shows the distribution of heat transfer among the passes. High heat transfer in the first pass of the thermal oil heater can be attributed to the high temperature radiation heat transfer. Difference in heat transfer of second pass and third pass is mainly due to higher heat transfer area and higher temperature difference of second pass. It can be also seen that the heat transfer in second pass is higher than the first pass at higher fuel firing rate. This is mainly due to higher heat transfer area of the second pass.

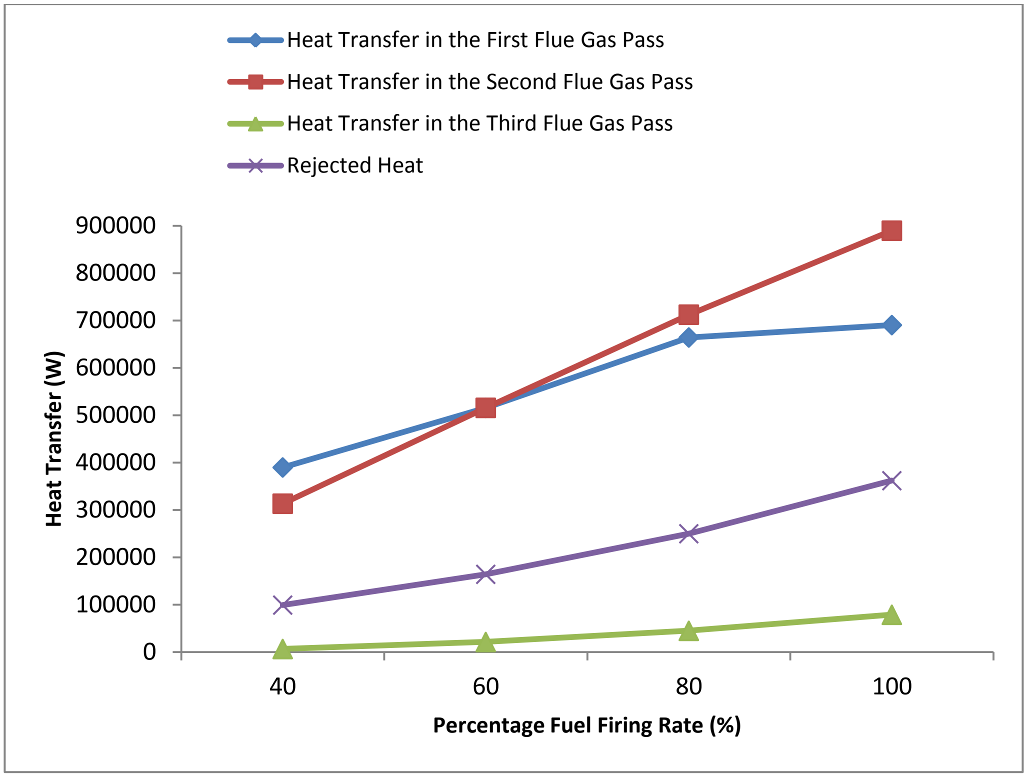

Fig. 9: Heat rate v/s Firing Rate

8.3 Effect of thermal oil Inlet temperature on the performance of Thermal oil heater

Different processes require different thermal oil temperature and thermal oil inlet temperature is varied to meet the requirement of process. Thermal oil heater is simulated with different thermal oil inlet temperature to study the effect of thermal oil temperature on the performance of thermal oil heater.

The effect of thermal oil inlet temperature on the flue gas outlet temperature and thermal oil outlet temperature has been plotted in Fig. 10. This shows increase in thermal oil outlet temperature with increase in thermal oil inlet temperature. The increase in thermal oil temperature has insignificant effect on heat transfer due to minor change in mean temperature difference. Due to this effect, thermal oil outlet temperature linearly varies with thermal oil inlet temperature. Small change in the flue gas temperature can be seen, this is mainly attributed to minor change in mean temperature difference. Flue gas outlet temperature increases with increase in thermal oil inlet temperature.

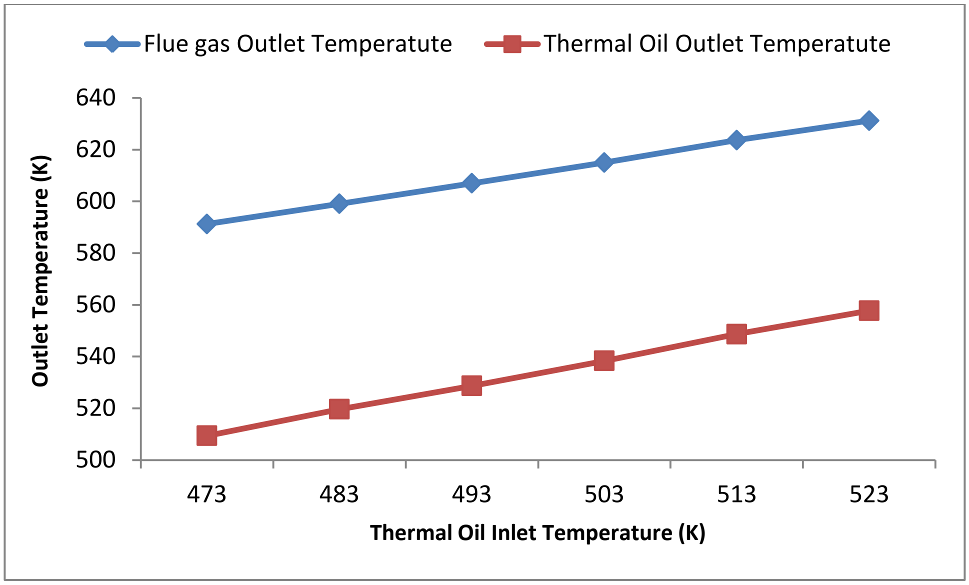

Fig. 10: Outlet temperature v/s Thermal oil inlet temperature

Fig. 11 shows the effect of thermal oil inlet temperature on the heat transfer rate of the different section of thermal oil heater. It shows insignificant change in the first pass of thermal oil heater, as this section has very high mean temperature difference and small change in thermal oil inlet temperature has insignificant impact on mean temperature difference. It has some effect in second & third pass of the thermal oil heater, as these section operate with relatively lower mean temperature difference.

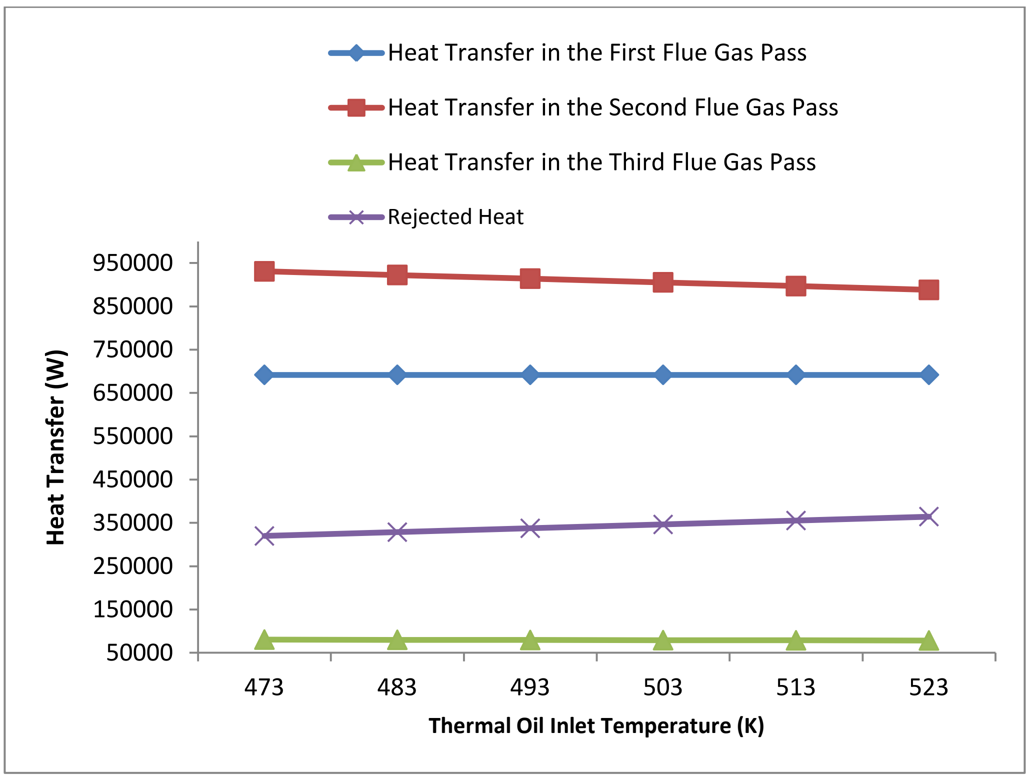

Fig. 11: Heat rate v/s Thermal oil inlet temperature

9. CONCLUSION

The thermal simulation model presented gives highly accurate results which are in accordance with the experimental observations. The maximum error in the temperature encountered was 4.38%. The generalized model can be incorporated in thermal design of industrial Thermal Oil Heaters. The model helps in predicting and studying the behavior of the system under varying operating conditions.

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