MODELING AND SIMULATION OF A FIRE TUBE BOILER

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ABSTRACT

A mathematical model is developed for simulating the steady state performance of the fire tube boiler in Hutteen General Company. It is a TUBOX package boiler with capacity of 16 ton steam per hour and operated with steam temperature and pressure of 158 °C (saturated temperature) and 6 bar respectively.

The boiler system is divided–for the convenience of analysis-into three zones according to its physical construction, and the energy balance is applied to each zone to form the sub-system models; finally all the sub-system models are coupled together to form a complete system model for the steady state operation for the boiler unit.

A set of empirical correlations has been employed for the evaluation of heat transfer and physical properties to determine the system parameters. The validity of the model and the assumptions used in modeling have been tested by running the program using the design input variables taken from the manufacturer manuals, and the simulated results have been compared with that of design data. Also the simulated results have been checked with some actual operation data taken from the data sheets of the boiler operation.

The effects of the fuel flow rates on the temperature profile (flame/gas and water/steam) and steam quality profile was studied for fire tube boiler.

INTRODUCTION

Boiler is a device used for generating steam for power plant, process use or heating purposes, and hot water for heating purposes or hot water supply. For simplicity's sake it is customary to consider the boiler as a steam procedure.

Boilers are designed to transmit heat from an external combustion source (usually fuel combustion) to a fluid contained within the boiler itself. The steam, or hot water, must be delivered in the desired condition –with respect to pressure, temperature, and quality- and at the desired rate. For economy's sake, the heat should be generated and delivered with minimum losses [1,2].

The heat generating unit includes a furnace (or combustion chamber), in which the fuel is burned. By definition, a boiler technically includes only the containing vessel and convection heating surfaces. With the advent of water-cooled furnace walls, superheaters, air heaters, and economizers, the term "steam generator" was evolved to serve as a better description of the apparatus. When the furnace is integral, the term "boiler" is generally understood to be descriptive of the heat generating unit. The heat output rate (steam or hot water generated per hour) depends upon extent of combustion of the furnace fuel, extent of the heating surface, distribution of the heating surface into prime (radiant) and secondary (convection) area, and circulation of steam or water and of combustion products [3,4].

To support combustion it is necessary to supply a quantity of air and to remove the products of combustion by means of a draft. When natural draft (chimney or stack effect) is insufficient, a draft fan (either forced, or induced, or both) is used [5].

The aim of this work is to study the temperature distribution for flame/gas and water/steam in the furnace, fire tubes and smoke tubes. Also study the steam quality distribution in the boiler.

Boiler Configuration and Mathematical Model

The TUBOX package fire tube boiler contain a cylindrical shell with cylindrical internal furnace built into the right of the convection part[6]. it is consist of three passes for gases: furnace, fire tubes and smoke tubes. The fuel oil is burned in the front section of the furnace or combustion chamber and the combustion product flow back and enters the rear combustion chamber, then flow through the tube passes to the smoke box and discharge into the chimney. The technical data of the boiler are shown in appendix (Table 1).

The following general assumptions are used in order to facilitate the mathematical formulation of the system:

1. Each zone is treated as a distributed one-dimensional system.
2. The flame is taken to be of constant diameter so that its shape is cylindrical.
3. The continuity of the mass flow rate and temperature is considered as the boundary condition for fluid flow and heat transfer among the zones.
4. The potential and kinetic energies are negligible.
5. The combustion of fuel oil is complete.

The mathematical model of the boiler system should be sufficiently accurate to represent the behavior of the boiler and also sufficiently simple for easiness of application to simulate the real operation of the system.

Boiler Chamber

The specifications of the combustion chamber are shown in appendix (Table 2). Heat transfer in this zone of the boiler occurs largely by radiation from the flames and the flue gases but also significantly by convection. The radiative properties depend on its chemical nature, its concentration, and temperature. In the thermal range, radiation is significant only from the triatomic molecules H_2O, CO_2 and SO_2. The emissivity of such a gas is represented as a function of temperature and the product (PL) of the partial pressures (P) of water vapor and carbon dioxide (SO_2 composition is small and usually neglected) and the path of travel defined by the mean beam length (L)[7,8].

The overall flame length, F_L, is obtained from the following equation [9]:

$$F_L = 6D_o\left(1 + AF^*\right)\left(\frac{\rho_e}{\rho C_p}\right)^{1/2}\left(\frac{\rho_e}{\rho_{Sa}}\right)^{1/2} \tag{1}$$

where,

$$D_o = \frac{2\left[1 + P_{pa}\left(AF^*\right)\right]}{\left[\left(G_F + G_{pa}\right)\pi\rho_e\right]^{1/2}} \tag{2}$$

$$G_F + G_{pa} = 1414 + \frac{\left[P_{pa}\left(AF^*\right)\right]^2}{\left\{\frac{1 - P_{O_2}}{1.224} + \frac{P_{O_2}}{1.308}\right\}^{-1} 0.065} \tag{3}$$

$$\rho_e = \frac{1 + P_{pa}\left(AF^*\right)}{\frac{1}{0.67} + \frac{\left(1 - P_{O_2}\right)P_{pa}\left(AF^*\right)}{1.224} + \frac{P_{O_2}P_{pa}\left(AF^*\right)}{1.308}} \tag{4}$$

$$AF^* = \frac{\left[AF - \left(1 - P_{O_2}\right)P_{pa}(AF) - 4.31 P_{O_2}P_{pa}(AF)\right]}{\left[\frac{1}{0.67} + \frac{\left(1 - P_{O_2}\right)P_{pa}(AF)}{1.224} + \frac{P_{O_2}P_{pa}(AF)}{1.308}\right]} \tag{5}$$

The flame radiation heat transfer rate in the furnace is calculated as:

$$S_{11} = \sigma . Ar_o . \varepsilon_f . F . \left(T^4_{z+d_{z0}} - T^4_s\right) \tag{6}$$

The gas radiation heat transfer rate is calculated as:

$$S_{12} = \sigma . A_{\eta} . \varepsilon_g . F . \left(T^4_{z+d_{z0}} - T^4_s\right) \tag{7}$$

The convective heat transfer rate is calculated as:

$$S_{13} = h_g . A_{\eta} . \left(T_{z+d_{z0}} - T_s\right) \tag{8}$$

The total heat transfer rate (by radiation and convection) in the furnace is:

$$S_1 = S_{11} + S_{12} + S_{13} \tag{9}$$

The heat generation rate is calculated as:

$$S_2 = \left(\dot{m}_{en,z+dz} - \dot{m}_{en,z}\right)\frac{H_F\left(1 - H_L\right)}{AF^*} \tag{10}$$

The sensible heat of entering and leaving air is calculated as:

$$S_3 = \dot{m}_{T,z} . Cp_a . \left(T_z - 298\right) + \dot{m}_{T,z+dz} . Cp_a \left(T_{z+dzn} - 298\right) \tag{11}$$

The total mass flow rate in the furnace is calculated as[9]:

$$\dot{m}_T = \dot{m}_{en} + \dot{m}_o \tag{12}$$

where,

$$\dot{m}_{en} = \left\{\frac{0.17z}{D_o}\left(\frac{\rho C_p}{\rho_e}\right)^{1/2}\left(\frac{\rho_{sa}}{\rho_e}\right)^{1/2} - 1\right\}\dot{m}_o \tag{13}$$

and

$$\dot{m}_o = \dot{m}_F + \dot{m}_{pa} \tag{14}$$

From the heat balance, the flame and gas temperature distribution in the combustion chamber may be calculated as:

$$T_{z+dzn} = (-S_1 + S_2 + S_3)/(\dot{m}_{T,z+dz} \cdot Cp_a) \tag{15}$$

At the equilibrium, the heat lost from the furnace equals to the heat absorbed by the water.

$$Q = \dot{m}_w \cdot Cp_w \cdot (T_{wo} - T_{wi}) = h_w \cdot A\eta \cdot (T_s - T_w) \tag{16}$$

where,

$$T_w = (T_{wo} + T_{wi})/2 \tag{17}$$

From the above equations the steam and water temperature were calculated in the combustion chamber.

In order to evaluate the tube wall temperature (T_s), the heat transfer rate from the inside surface of the furnace (at a temperature T_s) to the outside of the furnace (at a water temperature T_w) can be expressed as[10]:

$$S_1 = \frac{T_s - T_w}{\dfrac{1}{h_w \cdot A\eta} + \dfrac{d_i \ln(d_o/d_i)}{2\pi k}} \tag{18}$$

Fire Tubes

The specifications of the fire tube are shown in appendix (Table 3). The fire tubes in the present analysis were considered as two sub-zones:

The Flame Zone. When the overall flame length longer than the boiler length ($F_L > L_{Boiler}$). In this zone, both the flame and gas radiation heat transfer are equal to zero ($S_{11} = 0$ & $S_{12} = 0$), but the heat generation (S_2) is present. The other equations are the same in the furnace zone.

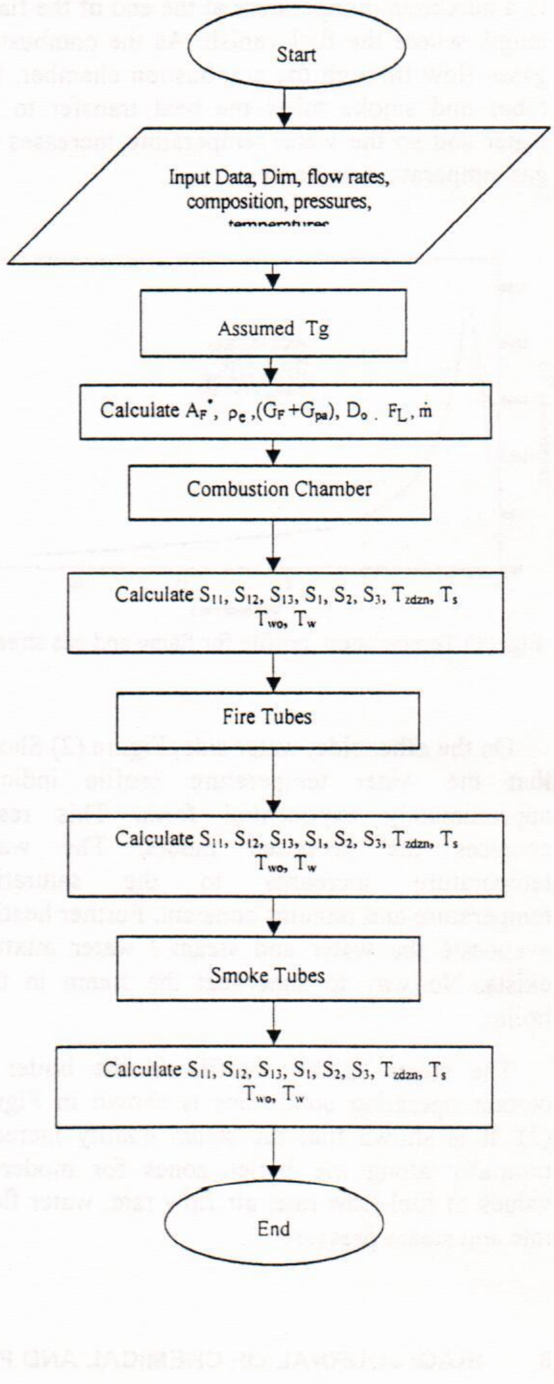
The Gas Zone. When the overall flame length shorter than the boiler length ($F_L < L_{Boiler}$). In this zone, both the flame radiation heat transfer and the heat generation are equal to zero ($S_{11} = 0$ & $S_2 = 0$), but the gas radiation heat transfer (S_{12}) is present. The other equations are the same in the furnace zone.

Smoke Tubes. The specifications of the smoke tubes are shown in appendix (Table 4). This zone is similar to the nonflame zone of the fire tubes where the flame radiation heat transfer and the heat generation are equal to zero. The other equations are the same in the furnace zone.

Computer Program

The calculation procedures were carried out with practically no restriction on difficulty and with the main objective of accuracy. A computer program is developed to calculate the temperature distribution and heat transfer in each part of the boiler in order to find the effects of various input parameters on the normal operation of the boiler.

The computer program, written in Quick Basic Language consists of a main program and many subroutines and functions. The flow chart of the main program is shown below.



RESULTS AND DISCUSSION

The boiler system was divided into three interactive zone, namely; combustion chamber zone, fire tubes zone, smoke tubes zone. The output results were represented as temperature profiles for flame/gas side , steam / water side and steam quality through the boiler zones which are indicated as distance in the figures showing these profiles. Figure (1) illustrates a typical temperature profile through the boiler. As shown in this figure, the gas temperature increases sharply due to heat generated in the first section of the combustion chamber zone. The heat liberated due to combustion of the fuel in this section is transferred to the water through the combustion gases. Consequently the gas temperature increases to a maximum temperature at the end of the flame length where the fuel vanish. As the combustion gases flow through the combustion chamber, fire tubes and smoke tubes the heat transfer to the water and so the water temperature increases the gas temperature decreases.

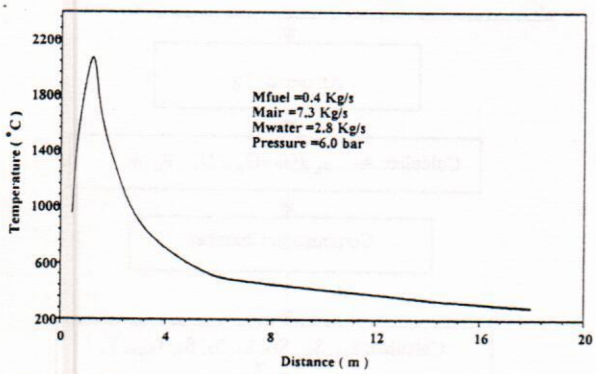


Fig. (1) Temperature profile for flame and gas stream

On the other side, water side, Figure (2) Shows that the water temperature profile indicate approximately exponential form. This result accesses the proposed model. The water temperature increases to the saturation temperature and remains constant. Further heating evaporate the water and steam / water mixture exists. No way to superheat the steam in this boiler.

The steam quality profile in the boiler at certain operating conditions is shown in Figure (3). It is shown that the steam quality increase normally along the boiler zones for moderate values of fuel flow rate, air flow rate, water flow rate and steam pressure.

The simulated parameters were selected and tested according to the design and the practical operation data of the boiler. Moreover, in order to check the validity of the present model and the accuracy of the simulation and computation of the program, the simulated results are compared in the previous work[9].

The most measurable value used in the comparison is the maximum flame temperature in the combustion chamber. The simulated results indicate a good agreement with the previous work. Also the same results were found about the temperature profile of water and steam quality.

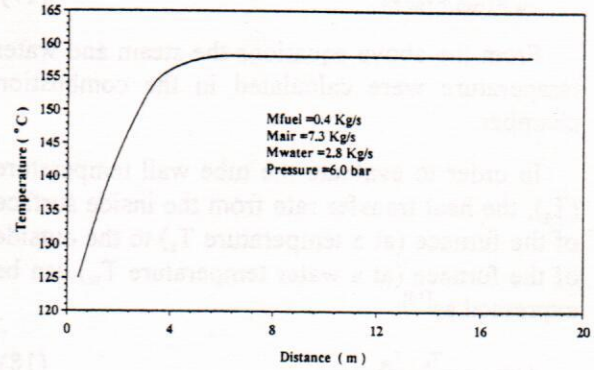


Fig. (2) Temperature profile for water and steam stream

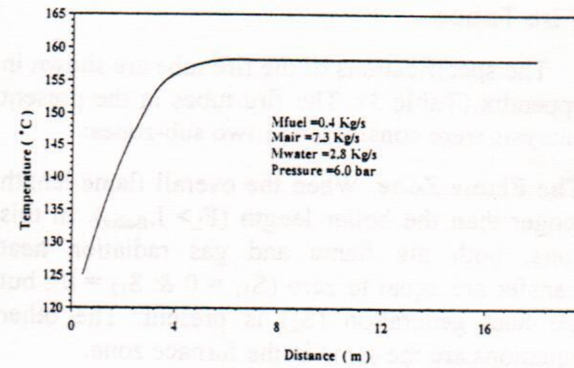


Fig. (3) Steam quality profile

Effect of Fuel Flow Rate

The general effect of fuel flow rate on the boiler operation is to increase all the temperatures in the boiler, but it mostly affects the temperature of the radiation zone due to the formation of soot which increases the luminosity of the flame. The effect of variation of fuel flow rate on the temperature profiles of flame and gas is shown in Fig. (4) for certain values of air flow rate and water flow rate. It is shown that the increase in fuel flow rate leads to an increase in the temperature of the flame and gas for the whole boiler zones in the range of fuel flow rate studied in this work. Also the rate of heat transfer in all zones becomes higher with larger fuel flow rates.

Figure (5) shows the effect of increase in fuel flow rate on the water and steam temperature profile in the various zones of the boiler. It is clear that the increase in fuel flow rate will increase the flame and gases temperature, which results in the acceleration on reaching to the saturation temperature.

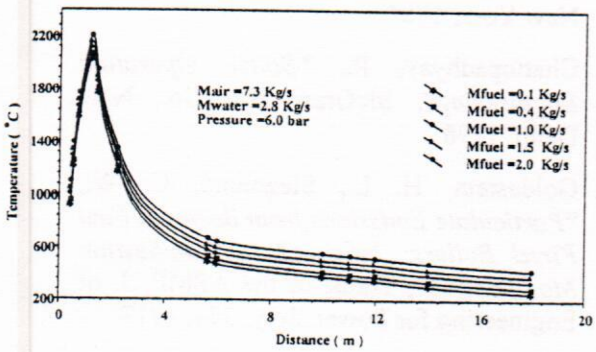


Fig. (4) Effect of fuel flow rate on flame and gas temperature profile

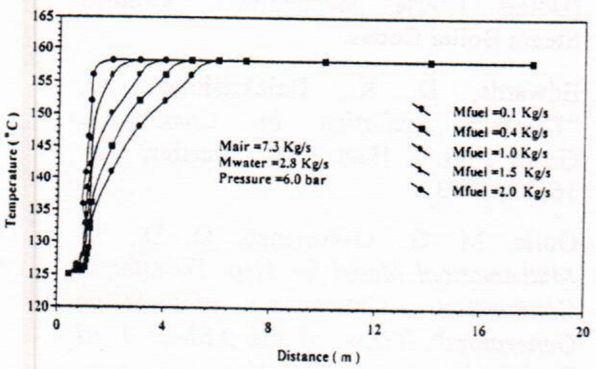


Fig. (5) Effect of fuel flow rate on water and steam temperature profile

Figure (6) shows the steam quality profile in the boiler for different values of the fuel flow rates . The steam quality increases normally along the boiler zones for moderate value of fuel flow rate. The steam quality increase with increase fuel flow rates.

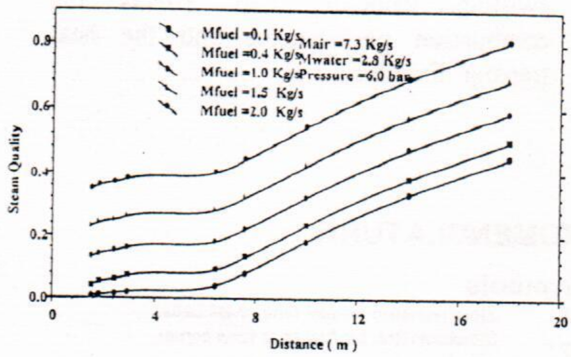


Fig. (6) Effect of fuel flow rate on the steam quality

CONCLUSIONS

The following conclusions are derived from the present work:

1. The heat absorption through the furnace wall increases with the increase in the rate of fuel consumption. After maximum value is reached, any increase in the rate of fuel consumption does not lead to higher heat absorption. It is because of the incomplete combustion, or there may be over-heating, and the flame may exceed the furnace.
2. The rate of heat transfer or heat absorption through the furnace wall has a certain value at the first part of the furnace (near the burner end). It increases with the increase of the distance from the burner. However, after maximum value, it decreases till the end of the boiler.
3. The excessive increase in fuel flow rate for a constant load of the boiler may lead to the so called the boiling crisis which leads to the tubes failure as result of thermal stresses.

Recommendations for Further Work

The recommendations for further research in this field are presented as follows:

1. Recovering the thermal energy from the exhaust gases to preheat the inlet air to the furnace or to increase the steam temperature. This will reduce the energy loss from the steam.
2. Studying the effect of dissociation during the combustion process, and the effect of soot concentration on the heat transfer process.

3. Study the effect of the mixing rate of the mixture of the fuel and air by inducing a swirling velocity. This affects the combustion performance and the heat transfer directly.

NOMENCLATURE

Symbols

AF	Stoichiometric air-fuel ratio, mass basis.	
AF*	Stoichiometric air-fuel ratio for a burner (Eq. 1).	
Ar_i	Surface area based on furnace diameter	m^2
Ar_o	Surface area based on flame diameter	m^2
Cp	Specific heat.	J/kg K
d	Diameter.	m
D_o	Equivalent burner diameter.	
F	View factor.	
F_L	Flame length.	m
G	Momentum flow rate.	kg m/s^2
h	Heat transfer coefficient.	W/m^{2}K
H_F	Gross heating value of fuel.	kJ/kg
H_L	Hydrogen loss percentage basis.	
k	Thermal conductivity.	W/m K
$\dot{m}$	Mass flow rate.	kg/s
$\dot{m}_o$	Mass flow rate of fuel and primary air	kg/s
P_{O_2}	Fraction of primary air replaced by pure oxygen, mass basis.	
P_{pa}	Fraction stoichiometric air as primary, mass basis.	
Q	Heat transfer rate.	W
S_1	Total heat transfer rate.	W
S_{11}	Flame radiation heat transfer rate.	W
S_{12}	Gas radiation heat transfer rate.	W
S_{13}	Convective heat transfer rate.	W
S_2	Heat generation rate.	W
S_3	Sensible heat of entering and leaving air.	W
T	Temperature.	K
z	Axial position relative to burner	m

Greek Symbols

σ	Stefan-Boltzmann Constant (5.667×10^{-8})	W/m^2 K^4
ε	Emissivity	
ρ	Density	kg/m^3
ρ_e	Equivalent fuel-gas density	

Subscripts

a	Air
cp	Combustion products
z	Film thickness
en	Entrained
f	Flame
F	Fuel
g	Gas
i	Inside
o	Outside
pa	Primary air
s	Surface
sa	Secondary air
T	Total
t	Tube
w	Water
z	Axial position z

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REFERENCES

1. Shields, C. D., "*Boilers*", McGraw-Hill Co., New York, 1961.
2. Austin, G. T., "Shreve's Chemical Process Industries", 5th Edition, McGraw-Hill Co., New York, 1984.
3. Chattopadhyay, P., "*Boiler Operation Engineering*", McGraw Hill Co., New Delhi, 1998.
4. Goldestein, H. L., Siegmund, C. W., "*Particulate Emissions from Residual Fuel Fired Boilers: Influence of Combustion Modification*", Trans. of the ASME, J. of Engineering for Power, July, 371, 1977.
5. Gupta, O. P., "*Elements of Fuels, Furnaces and Refractories*", 3rd Edition, Khanna Publishers, 1995.
6. Operation and Maintenance Manual for Hutteen General Company, file 1,2 and 3 (Boiler House Mechanical), Swedish Steam Boiler Codes.
7. Edwards, D. K., Balakrishnan, A., "*Thermal Radiation by Combustion Gases*", Int. J. Heat Mass Transfer, Vol. 16, 25, 1973.
8. Gulic, M. G., Gvozdenac, D. D., "*A Mathematical Model for Heat Transfer in Combustion Chambers of Steam Generators*", Trans. of the ASME, J. of Engineering for Power, Vol. 103, July, 545, 1981.
9. Gorog, J. P., "*Heat Transfer from Flames in a Rotary Kiln*", Metallurgical Transactions B, Vol. 14B, September, 411, 1983.
10. Holman, J. P., White, P. R., "*Heat Transfer*", 7th Edition, McGraw Hill Co., London, 1992.

Table (1) Technical data of the boiler

steam capacity	16 ton/hr
steam temperature	158 °c
steam pressure	6 bar
feed water temperature	100 °c
air temperature	25 °c
water flow rate	2.8 kg/s
air flow rate	7.3 kg/s
water volume at normal water level	14.3 m^3
shell diameter	2800 mm
shell length	6150 mm

Table (2) Specifications of combustion chamber

Furnace:	
outside diameter (mm)	1250
thickness (mm)	7
length (mm)	5430
surface area (m^2)	21.324
Burner	
Number	1
type	SAACK rotary cup atomizing
fuel flow rate (kg/s)	0.4
Fuel	
type	fuel oil
specific gravity at 15/15°c	0.844
viscosity at room temperature (ck)	85
flash point (°c)	75
gross calorific value (kj/kg)	44908
net calorific value (kj/kg)	42178
theoretical flame temperature (°c)	1900
maximum freezing point (°c)	15
maximum storage temperature (°c)	20
atomizing temperature (°c)	(125-140)

Table (3) Specifications of fire tubes

Number	111
Length (mm)	5341
Thickness (mm)	3.6
Outside diameter (mm)	76.1
Surface area (m^2)	141.736

Table (4) Specifications of smoke tubes

Number	181
Length (mm)	6064
Thickness (mm)	3.6
Outside diameter (mm)	60.3
Surface area (m^2)	207.924