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Simplified Applicable Model for Fire Tube Boiler

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Abstract

This research aims to present a simplified mathematical model to predict the performance of fire tube boilers, taking into account the necessity of knowing the components of exhaust gases and the extent of their compatibility with environmental laws and requirements. The model shown is for a horizontal, three-pass, wet-back fire tube boiler at steady-state, steady-flow operation. It is concluded from the applicability of the model for different boiler capacity ratings that the results are simplified and important for the boiler manufacturers to predict the performance and make the choice to modify the proposed design to achieve certain needs.

Keywords

Thermal, Environmental, Boiler, Model

1. Introduction

Fire tube boilers are used in many industrial applications, and it is formed from cylindrical drum containing main fire tube (combustion chamber/furnace), smoke chambers, and smoke tubes. The operating principle for the fire tube boiler is to surround water over the internal components while the hot gases flow inside. For details about boiler types, the reader is advised to see Boiler 101 article, American Boiler Manufacturers Association ABMA. The boiler's manufacturers need a simplified tool to predict the boiler performance as a pre-manufacturing becomes in the process. Ortiz [1] developed a model to analyze the boiler performance regardless of the combustion products. Komarov [2] studied the effect of burner conditions on the performance of fire tube boiler. Beyne [3] developed a model to predict the peak boiler capacity. The model did not consider the combustion products.

Kelin [4] presented a model for design optimization without flue gas species.

If previous research is reviewed to the extent available, the researcher can notice that the mathematical models presented were not intended to predict the components of exhaust gases resulting from the combustion process, and that these simulation models may be difficult to deal with by manufacturing engineers in the pre-manufacturing stages. Therefore, this work proposes simplified simulation model for performance prediction for fire tube boilers, considering the necessity of knowing the exhaust gases and the extent of their compatibility with environmental laws and requirements. The model is for a horizontal, three-pass, wet-back fire tube boiler at steady-state, steady-flow operation.

2. Mathematical Model

2.1. Thermal Analysis

The fire tube boiler is divided into five interconnected subsystems. These subsystems are:

a) Main Fire Tube;
b) First Smoke Chamber;
c) First Smoke Tubes;
d) Second Smoke Chamber;
e) Second Smoke Tubes.

Thermal analysis was performed on each subsystem by applying the first law of thermodynamics [5] and heat transfer correlations [6]. The main objective of thermal analysis is to determine the rate of heat transfer, temperature and flow resistance for each subsystem.

a) Main Fire Tube:

The heat is transferred from the main fire tube to the boiling water mainly by radiation from the formed illuminated flame to the inner surface of the main fire tube. Also, convection from the generated hot combustion gases contributes to the heat transfer to the main fire tube. The thermal analysis of the main fire tube is based on the following assumptions:

1) The combustion process occurs in the main fire tube and is governed by chemical equilibrium [7].

2) The flame and combustion gases are assumed to be in bulk status with uniform temperature and thermophysical properties.

3) The temperature of inner surface of the main fire tube is mathematically negligible compared with the gas temperature in the radiation formula.

$$\dot{Q}_{input} = \dot{m}_f CV \eta_{cc} \tag{1}$$

$$\dot{m}_g = \left(1 + AF\right)\dot{m}_f \tag{2}$$

$$\varepsilon_{wf} = \frac{1}{\frac{1}{\varepsilon_w} + \frac{A_{mft}}{A_{flame}}\left(\frac{1}{\varepsilon_f} - 1\right)} \tag{3}$$

$$\dot{Q}_r = \varepsilon_{wf}\sigma A_{mft}T_g^4 \tag{4}$$

$$V_{mft} = \frac{\dot{m}_g}{\rho_g\left(\frac{\pi D_{mft}^2}{4}\right)} \tag{5}$$

$$Re_{mft} = \frac{\rho_g V_{mft} D_{mft}}{\mu_g} \tag{6}$$

$$h_{mft} = 0.023\left(\frac{k_g}{D_{mft}}\right)\left(Re_{mft}^{0.8}\right)\left(Pr_g^{0.3}\right) \tag{7}$$

$$\dot{Q}_c = A_{mft}h_{mft}\left(T_g - T_{sat}\right) \tag{8}$$

$$\dot{Q}_{input} = \dot{Q}_r + \dot{Q}_c + \dot{m}_g Cp_g\left(T_g - T_{ref}\right) \tag{9}$$

$$f_{mft} = \left(1.58\ln\left(Re_{mft}\right) - 3.28\right)^{-2} \tag{10}$$

$$\Delta\dot{P}_{mft} = \frac{f_{mft}L_{mft}V_{mft}^2\rho_g}{2D_{mft}} \tag{11}$$

*Thermophysical properties are determined at T_g.

4) For all the following subsystems, the combustion gases generated from the combustion process in the main fire tube flow through the rest of subsystems in frozen flow. The heat is transferred mainly by convection and radiation from the flowing combustion gas to the boiling water through the subsystem's surfaces.

b) First Smoke Chamber:

$$\dot{Q}_{rcc1} = \varepsilon_{cc1}\sigma A_{cc1}\left(\overline{T}_{cc1}^{\,4} - T_{sat}^4\right) \tag{12}$$

$$V_{cc1} = \frac{\dot{m}_g}{\rho_g\left(\frac{\pi D_{cc1}^2}{4}\right)} \tag{13}$$

$$Re_{cc1} = \frac{\rho_g V_{cc1} D_{cc1}}{\mu_g} \tag{14}$$

$$h_{cc1} = 0.023\left(\frac{k_g}{D_{cc1}}\right)\left(Re_{cc1}^{0.8}\right)\left(Pr_g^{0.3}\right) \tag{15}$$

$$\dot{Q}_{ccc1} = A_{cc1}h_{cc1}\Delta T_{lm} \quad \Delta T_{lm} = \frac{\left(T_g - T_{sat}\right) - \left(T_{cc1} - T_{sat}\right)}{\ln\left(\frac{T_g - T_{sat}}{T_{cc1} - T_{sat}}\right)} \tag{16}$$

$$\dot{m}_g Cp_g\left(T_g - T_{cc1}\right) = \dot{Q}_{rcc1} + \dot{Q}_{ccc1} \tag{17}$$

$$f_{cc1} = \left(1.58\ln\left(Re_{cc1}\right) - 3.28\right)^{-2} \tag{18}$$

$$\Delta\dot{P}_{cc1} = \frac{f_{cc1}L_{cc1}V_{cc1}^2\rho_g}{2D_{cc1}} \tag{19}$$

*Thermophysical properties are determined at $\overline{T_{cc1}}$.

c) First Smoke Tubes:

$$\dot{Q}_{r1} = \varepsilon_1 \sigma A_1 \left(\overline{T_{g1}}^4 - T_{sat}^4 \right) \tag{20}$$

$$V_1 = \frac{\dot{m}_g}{n_{t1} \rho_g \left(\frac{\pi D_1^2}{4} \right)} \tag{21}$$

$$Re_1 = \frac{\rho_g V_1 D_1}{\mu_g} \tag{22}$$

$$h_1 = 0.023 \left(\frac{k_g}{D_1} \right) \left(Re_1^{0.8} \right) \left(Pr_g^{0.3} \right) \tag{23}$$

$$\dot{Q}_{c1} = A_1 h_1 \Delta T_{lm} \quad \Delta T_{lm} = \frac{\left(T_{cc1} - T_{sat} \right) - \left(T_{g1} - T_{sat} \right)}{\ln \left(\frac{T_{cc1} - T_{sat}}{T_{g1} - T_{sat}} \right)} \tag{24}$$

$$\dot{m}_g C p_g \left(T_{cc1} - T_{g1} \right) = \dot{Q}_{r1} + \dot{Q}_{c1} \tag{25}$$

$$f_1 = \left(1.58 \ln \left(Re_1 \right) - 3.28 \right)^{-2} \tag{26}$$

$$\Delta \dot{P}_1 = \frac{f_1 L_1 V_1^2 \rho_g}{2 D_1} \tag{27}$$

*Thermophysical properties are determined at $\overline{T_{g1}}$.

d) Second Smoke Chamber:

$$\dot{Q}_{rcc2} = \varepsilon_{cc2} \sigma A_{cc2} \left(\overline{T_{cc2}}^4 - T_{sat}^4 \right) \tag{28}$$

$$V_{cc2} = \frac{\dot{m}_g}{\rho_g \left(\frac{\pi D_{cc2}^2}{4} \right)} \tag{29}$$

$$Re_{cc2} = \frac{\rho_g V_{cc2} D_{cc2}}{\mu_g} \tag{30}$$

$$h_{cc2} = 0.023 \left(\frac{k_g}{D_{cc2}} \right) \left(Re_{cc2}^{0.8} \right) \left(Pr_g^{0.3} \right) \tag{31}$$

$$\dot{Q}_{ccc2} = A_{cc2} h_{cc2} \Delta T_{lm} \quad \Delta T_{lm} = \frac{\left(T_{g1} - T_{sat} \right) - \left(T_{cc2} - T_{sat} \right)}{\ln \left(\frac{T_{g1} - T_{sat}}{T_{cc2} - T_{sat}} \right)} \tag{32}$$

$$\dot{m}_g C p_g \left(T_{g1} - T_{cc2} \right) = \dot{Q}_{rcc2} + \dot{Q}_{ccc2} \tag{33}$$

$$f_{cc2} = \left(1.58 \ln \left(Re_{cc2} \right) - 3.28 \right)^{-2} \tag{34}$$

$$\Delta \dot{P}_{cc2} = \frac{f_{cc2} L_{cc2} V_{cc2}^2 \rho_g}{2 D_{cc2}} \tag{35}$$

*Thermophysical properties are determined at $\overline{T}_{cc2}$.

e) Second Smoke Tubes:

$$\dot{Q}_{r2} = \varepsilon_2 \sigma A_2 \left(\overline{T}_{g2}^{\,4} - T_{sat}^4 \right) \tag{36}$$

$$V_2 = \frac{\dot{m}_g}{n_{t2} \rho_g \left(\dfrac{\pi D_2^2}{4} \right)} \tag{37}$$

$$Re_2 = \frac{\rho_g V_2 D_2}{\mu_g} \tag{38}$$

$$h_2 = 0.023 \left(\frac{k_g}{D_2} \right) \left(Re_2^{0.8} \right) \left(Pr_g^{0.3} \right) \tag{39}$$

$$\dot{Q}_{c2} = A_2 h_2 \Delta T_{lm} \quad \Delta T_{lm} = \frac{\left(T_{cc2} - T_{sat} \right) - \left(T_{g2} - T_{sat} \right)}{\ln \left(\dfrac{T_{cc2} - T_{sat}}{T_{g2} - T_{sat}} \right)} \tag{40}$$

$$\dot{m}_g C p_g \left(T_{cc2} - T_{g2} \right) = \dot{Q}_{r2} + \dot{Q}_{c2} \tag{41}$$

$$f_2 = \left(1.58 \ln \left(Re_2 \right) - 3.28 \right)^{-2} \tag{42}$$

$$\Delta \dot{P}_2 = \frac{f_2 L_2 V_2^2 \rho_g}{2 D_2} \tag{43}$$

*Thermophysical properties are determined at $\overline{T}_{g2}$.

Then the boiler efficiency is determined by:

$$\eta = 100.0 \frac{m_{st} \left(h_{st} - h_w \right) = \sum \text{Heat Transfer}}{\dot{Q}_{input}}$$

2.2. Environmental Impact

The combustion process that takes place in the main fire tube is expressed according to the following chemical reaction formula:

$$\begin{aligned} & \mathrm{C}_x \mathrm{H}_y + z \left(\mathrm{O}_2 + 3.76 \mathrm{N}_2 \right) \\ & \rightarrow n_{\mathrm{O}} \mathrm{O} + n_{\mathrm{H}} \mathrm{H} + n_{\mathrm{OH}} \mathrm{OH} + n_{\mathrm{H_2O}} \mathrm{H_2O} + n_{\mathrm{N}} \mathrm{N} + n_{\mathrm{NO}} \mathrm{NO} + n_{\mathrm{CO}} \mathrm{CO} \\ & \quad + n_{\mathrm{CO_2}} \mathrm{CO_2} + n_{\mathrm{O_2}} \mathrm{O_2} + n_{\mathrm{H_2}} \mathrm{H_2} + n_{\mathrm{N_2}} \mathrm{N_2} \end{aligned}$$

where the combustion products are found based on the chemical equilibrium model, where the number of moles for the combustion product is governed by the following set of equations:

$$n_{\mathrm{O}} = K p_1 \left(\frac{P_3}{n_t} \right)^{-0.5} \left(n_{\mathrm{O_2}} \right)^{0.5} \tag{44}$$

$$n_{\mathrm{OH}} = K p_3 \left(n_{\mathrm{O_2}} \right)^{0.5} \left(n_{\mathrm{H_2}} \right)^{0.5} \tag{45}$$

$$n_{\mathrm{N}} = K p_5 \left(\frac{P_3}{n_t} \right)^{-0.5} \left(n_{\mathrm{N_2}} \right)^{0.5} \tag{46}$$

$$n_{CO} = Kp_9 (n_C)(n_{O_2})^{0.5} \tag{47}$$

$$N_H = y = n_H + n_{OH} + 2n_{H_2O} + 2n_{H_2} \tag{48}$$

$$N_N = 2 * 3.76z = n_N + n_{NO} + 2n_{N_2} \tag{49}$$

$$n_H = Kp_2 \left(\frac{P_3}{n_t}\right)^{-0.5} (n_{H_2})^{0.5} \tag{50}$$

$$n_{H_2O} = Kp_4 \left(\frac{P_3}{n_t}\right)^{0.5} (n_{H_2})(n_{O_2})^{0.5} \tag{51}$$

$$n_{NO} = Kp_6 (n_{N_2})^{0.5} (n_{O_2})^{0.5} \tag{52}$$

$$n_{CO_2} = Kp_{10} (n_{O_2})(n_C) \tag{53}$$

$$N_O = 2z = n_O + n_{OH} + n_{H_2O} + n_{NO} + n_{CO} + 2n_{CO_2} + 2n_{O_2} \tag{54}$$

$$N_C = x = n_{CO} + n_{CO_2} \tag{55}$$

$$N_H = y = n_H + n_{OH} + 2n_{H_2O} + 2n_{H_2} \tag{56}$$

$$N_N = 2 * 3.76z = n_N + n_{NO} + 2n_{N_2} \tag{57}$$

*where the equilibrium constants depend on the combustion temperature.

2.3. Mechanical Design

The shell of fire tube boiler is subjected to inner hoop stress, which is calculated as:

$$\sigma = \frac{P_{st} * D_{shell}}{2x} \tag{58}$$

The mathematical equations with all heat transfer, thermodynamic, and chemical equilibrium data are solved through a visual FORTRAN program.

3. Case Studies

Three designs are presented by a boiler manufacturer, with steam capacities of 1, 2, and 3 Ton per Hour (TPH). These boilers will work under the following conditions:

Inlet Conditions: $T_w = 100^\circ\text{C}$, Compressed Liquid, $h_w = 418\ \text{kJ/kg}$;

Outlet Conditions: $P_{st} = 10\ \text{bar}(\text{g})$, Saturated Steam, $T_{sat} = 184.1^\circ\text{C}$, $h_{st} = 2781\ \text{kJ/kg}$.

For the metal surface of boiler components, the emissivities of various subsystems may be approximated to be:

$$\varepsilon_w = 0.95$$

$$\varepsilon_{cc1} = 0.8$$

$$\varepsilon_1 = 0.45$$

$$\varepsilon_{cc2} = 0.8$$

$$\varepsilon_2 = 0.2$$

The flame emissivity may be approximated to be:

$$\varepsilon_f = 0.95$$

The efficiency of combustion process may be approximated to be:

$$\eta_{cc} = 1$$

Natural Gas is chemically formulated as CH_4, while the Diesel fuel is chemically formulated as $C_{12}H_{23}$.

The combustion process occurred at the stoichiometric conditions.

3.1. 1 TPH Boiler

Table 1 shows the results obtained from the model for the studied case (1 TPH Boiler), while the boiler dimensions and heat transfer areas are:

$$A_{mft} = \pi(0.55)(2.1) = 3.6285\ \text{m}^2$$

$$A_{cc1} = \frac{\pi}{4}\left[(0.99)^2 - (0.5)^2 + (0.99)^2 - (0.55)^2 - 20(0.051)^2\right] + \pi(0.99)(0.6)$$
$$= 2.931\ \text{m}^2$$

$$A_1 = \pi(20)(0.051)(2.15) = 6.89\ \text{m}^2$$

$$A_{cc2} = 1.2\ \text{m}^2$$

$$A_2 = \pi(20)(0.051)(2.9) = 9.293\ \text{m}^2$$

Table 1. Model results—boiler (1 TPH Boiler).

Parameter	Diesel Fuel	Natural Gas Fuel	Units
Total Heating Surface Area	23.941		m^2
Fuel Calorific Value "Calculated"	42.93	50.07	MJ/kg
Stoichiometric Air To Fuel Ratio "Calculated"	14.67	17.24	-
Fuel Flow Rate	60.81	52.2	kg/hr
Air Flow Rate	892.3	899.3	kg/hr
Exhaust Gas Flow Rate	953.1	951.4	kg/hr
Temperature in Main Fire Tube	962.3	962.5	˚C
Temperature at First Smoke Chamber Exit	515.7	515.3	˚C
Temperature at First Smoke Tubes Exit	273.8	273.6	˚C
Temperature at Second Smoke Chamber Exit	264.7	264.6	˚C
Temperature at Second Smoke Tubes Exit	207.7	207.7	˚C
Heat Transfer from Main Fire Tube	431.7	431.9	kW
Heat Transfer from First Smoke Chamber	136.6	136.5	kW
Heat Transfer from First Smoke Tubes	69.1	68.9	kW
Heat Transfer from Second Smoke Chamber	2.5	2.49	kW
Heat Transfer from Second Smoke Tubes	15.7	15.7	kW

Continued

Main Fire Tube Heat Contribution	65.76	65.8	%
First Smoke Chamber Heat Contribution	20.81	20.8	%
First Smoke Tubes Heat Contribution	10.52	10.5	%
Second Smoke Chamber Heat Contribution	0.38	0.38	%
Second Smoke Tubes Heat Contribution	2.4	2.4	%
Flow Resistance	5.9	5.9	mbar
Boiler Efficiency	90.3	90.35	%
NOx	3.27×10^{-3}	3.09×10^{-3}	%
CO_2	13.345	9.55	%
O_2	0.287	0.2632	%
CO	5.44×10^{-6}	4.07×10^{-6}	%
Hoop Stress	10,065,688		N/m^2

3.2. 2 TPH Boiler

Table 2 shows the results obtained from the model for the studied case (2 TPH Boiler), while the boiler dimensions and heat transfer areas are:

$$A_{mft} = \pi(0.62)(2.58) = 5.0253\ \text{m}^2$$

$$A_{cc1} = \frac{\pi}{4}\left[(1.05)^2 - (0.5)^2 + (1.05)^2 - (0.62)^2 - 36(0.051)^2\right] + \pi(1.05)(0.6)$$
$$= 3.74\ \text{m}^2$$

$$A_1 = \pi(36)(0.051)(2.6) = 15\ \text{m}^2$$

$$A_{cc2} = 1.2\ \text{m}^2$$

$$A_2 = \pi(36)(0.051)(3.4) = 19.6\ \text{m}^2$$

Table 2. Model results—boiler (2 TPH Boiler).

Parameter	Diesel Fuel	Natural Gas Fuel	Units
Total Heating Surface Area	43.97		m^2
Fuel Calorific Value "Calculated"	42.93	50.07	MJ/kg
Stochiometric Air To Fuel Ratio "Calculated"	14.67	17.24	-
Fuel Flow Rate	122.3	104.9	kg/hr
Air Flow Rate	1795.4	1809.05	kg/hr
Exhaust Gas Flow Rate	1916.7	1913.997	kg/hr
Temperature in Main Fire Tube	1061.8	1062.1	˚C
Temperature at First Smoke Chamber Exit	675.9	675.6	˚C
Temperature at First Smoke Tubes Exit	274.5	274.4	˚C
Temperature at Second Smoke Chamber Exit	269.6	269.5	˚C

Continued

Temperature at Second Smoke Tubes Exit	205.2	205.2	˚C
Heat Transfer from Main Fire Tube	795.5	796.2	kW
Heat Transfer from First Smoke Chamber	242.37	242.36	kW
Heat Transfer from First Smoke Tubes	234.13	233.8	kW
Heat Transfer from Second Smoke Chamber	2.7	2.7	kW
Heat Transfer from Second Smoke Tubes	35.6	35.55	kW
Main Fire Tube Heat Contribution	60.6	60.75	%
First Smoke Chamber Heat Contribution	18.46	18.46	%
First Smoke Tubes Heat Contribution	17.8	17.8	%
Second Smoke Chamber Heat Contribution	0.21	0.205	%
Second Smoke Tubes Heat Contribution	2.7	2.7	%
Flow Resistance	6	6	mbar
Boiler Efficiency	89.778	89.798	%
NOx	6.12×10^{-3}	5.86×10^{-3}	%
CO_2	13.345	9.55	%
O_2	0.286	0.2623	%
CO	4.813×10^{-5}	3.604×10^{-5}	%
Hoop Stress	74,038,461		N/m^2

3.3. 3 TPH Boiler

Table 3 shows the results obtained from the model for the studied case (3 TPH Boiler), while the boiler dimensions and heat transfer areas are:

$$A_{mft} = \pi(0.72)(2.75) = 6.22\ \text{m}^2$$

$$A_{cc1} = \frac{\pi}{4}\left[(1.2)^2 - (0.5)^2 + (1.2)^2 - (0.72)^2 - 50(0.0483)^2\right] + \pi(1.2)(0.6)$$
$$= 3.83\ \text{m}^2$$

$$A_1 = \pi(50)(0.0483)(2.6) = 19.73\ \text{m}^2$$

$$A_{cc2} = 1.2\ \text{m}^2$$

$$A_2 = \pi(50)(0.0483)(3.5) = 25.8\ \text{m}^2$$

Table 3. Model results—boiler (3 TPH Boiler).

Parameter	Diesel Fuel	Natural Gas Fuel	Units
Total Heating Surface Area	56.75		m^2
Fuel Calorific Value "Calculated"	42.93	50.07	MJ/kg
Stoichiometric Air To Fuel Ratio "Calculated"	14.67	17.24	-
Fuel Flow Rate	184.15	158	kg/hr

Continued

Air Flow Rate	2701.96	2724.3	kg/hr
Exhaust Gas Flow Rate	2886.1	2882.32	kg/hr
Temperature in Main Fire Tube	1104.7	1105.1	˚C
Temperature at First Smoke Chamber Exit	734.3	734.1	˚C
Temperature at First Smoke Tubes Exit	285.8	285.6	˚C
Temperature at Second Smoke Chamber Exit	282	281.8	˚C
Temperature at Second Smoke Tubes Exit	208	207.9	˚C
Heat Transfer from Main Fire Tube	1150.2	1151.5	kW
Heat Transfer from First Smoke Chamber	353.11	353.22	kW
Heat Transfer from First Smoke Tubes	397.1	396.42	kW
Heat Transfer from Second Smoke Chamber	3.2	3.19	kW
Heat Transfer from Second Smoke Tubes	61.84	61.6	kW
Main Fire Tube Heat Contribution	58.4	58.5	%
First Smoke Chamber Heat Contribution	17.9	17.93	%
First Smoke Tubes Heat Contribution	20.2	20.13	%
Second Smoke Chamber Heat Contribution	0.162	0.162	%
Second Smoke Tubes Heat Contribution	3.14	3.13	%
Flow Resistance	6.15	6.14	mbar
Boiler Efficiency	89.43	89.45	%
NOx	7.9×10^{-3}	7.45×10^{-3}	%
CO_2	13.345	9.55	%
O_2	0.285	0.2617	%
CO	8.4×10^{-5}	6.2×10^{-5}	%
Hoop Stress	61874995.4		N/m^2

4. Conclusion

It is concluded from the model applicability for different boiler capacity ratings that the results are simplified and important for the manufacturers to estimate the performance and modify the proposed designs to achieve certain needs. Also, the model results offer a quick tool for condition monitoring for the boiler and prediction for troubleshooting. The model addresses a relevant engineering problem by providing a tool for optimizing boiler design and predicting performance. The model's simplicity, compared to potentially complex CFD simulations, might make it attractive to manufacturers seeking accessible design tools.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

Symbol	Definition	Unit
$\dot{Q}_{input}$	Input energy to the boiler in form of fuel chemical energy	W
$\dot{m}_f$	Mass flow rate of fuel	kg/s
CV	Calorific value of fuel	J/kg
η_{cc}	Efficiency of combustion process	-
$\dot{m}_g$	Mass flow rate of exhaust combustion gases	kg/s
AF	Air to fuel mass ratio	-
ε_{wf}	Net emissivity between flame and inner surface of main fire tube	-
ε_w	Emissivity of inner surface of main fire tube	-
A_{mft}	Surface area of main fire tube	m^2
A_{flame}	Surface area of flame	m^2
ε_f	Emissivity of flame	-
$\dot{Q}$	Rate of heat transfer	W
σ	Stephan Boltzmann Radiation Constant	˚C
T	Temperature	K
V	Flow velocity	m/s
D	Diameter	m
ρ	Density	kg/m^3
Re	Reynolds number	-
μ	Dynamic viscosity	Pa·s
h	Convective heat transfer coefficient	W/m^2·K
k	Thermal conductivity	W/m·K
Pr	Prandtle number	-
T_{sat}	Saturation temperature of boiling water	K
Cp	Isobaric specific heat	J/kg·K
f	Friction factor	-
L	Length of main fire tube	m
ΔP	Flow resistance	Pa
T_{ref}	Reference Temperature	K
P	Pressure	Pa
x	Thickness	m
n_t	Number of tubes	-
n	Number of moles	moles
N	Number of atoms	atoms
z	Number of moles of air	moles

Continued

Subscripts	Definition
mft	Main Fire Tube
$cc1$	First Smoke Chamber
1	First Smoke Tubes
$cc2$	Second Smoke Chamber
2	Second Smoke Tubes
g	Combustion Gases
r	Radiation
c	Convection
st	Steam
w	Water
$shell$	Boiler Shell