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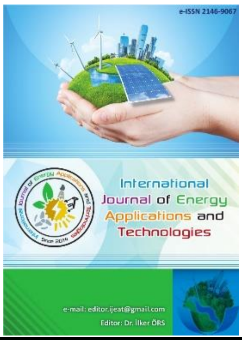

Original Research Article

Validation and simulation of furnace exit gas temperature and modelling of furnace slag thickness of oil fired boiler of power generating steam turbine

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ABSTRACT

This paper discusses on the study of validation and simulation of the furnace exit gas temperature and modeling of furnace slag thickness of oil fired boiler of power generating steam turbine unit of 323 MWe. Furnace exit gas temperature is an important operational boiler parameter. Its continuous monitoring and controlling is crucial to get reduction in fire side corrosion and fouling of furnace. Thermodynamic heat and mass balance model was developed to validate the furnace exit gas temperature measurement of the newly installed Infrared sensors at furnace exit. Furnace exit gas Temperature validation was performed at minimum and rated loading conditions of the boiler. The difference between measured and calculated furnace exit gas temperature was in the range of ± 20°C. Fifteen variables of boiler including steam turbine were selected at different operating conditions of the boiler to perform the simulation study of furnace exit gas temperature by using Excel solver module. The temperature difference of measured and simulated temperature remained within ± 5°C at minimum and rated loading conditions of the boiler due to strong statistical co-relation among the selected variables. Modeling of furnace slag thickness was done in relation to the increase in furnace exit gas temperature. Analysis shows that 15 mm thick layer of ash deposit on furnace walls can increase furnace exit gas temperature by 149°C. Sensitivity analysis of furnace exit gas temperature at boiler rated loading condition was also performed in-order to analyse the impact of boiler crucial parameters on furnace exit gas temperature.

Keywords: Furnace exit gas temperature, Furnace heat and mass balance, Furnace fouling and slagging, Simulation of boiler furnace exit gas temperature, Sensitivity analysis

1. Introduction

Utility and Industrial boilers are designed to match their duty with typical temperature profile through their components sizing. Operation of boiler close to its design temperature profile gives better operational efficiency of boiler and also ensures long operating life of boiler components. Among various heat absorbing surfaces of boiler, the furnace absorbs the highest proportion of the supplied heat to the boiler. The furnace under study can absorb up to 47% of the total heat supplied to the boiler based on the testing of boiler at steam turbine all Valves Wide Opening (VWO). Monitoring and controlling of Furnace Exit Gas Temperature (FEGT) is very important to get the first hand information of furnace heat sharing to the boiler. There are numerous factors that affect furnace performance and its duty. If furnace absorbs lesser heat than its design due to furnace fireside or water side fouling, furnace exit gas temperature will increase and consequently excessive water spray will be needed to control and maintain the steam turbine terminal conditions. Excessive quantity of water spray of super heater and re-heater deteriorates steam cycle thermal efficiency. Moreover, operation of boiler at higher furnace exit gas temperature than design increases the potential of overheating, fouling and fire side corrosion of boiler tubes following boiler tube leak incidents, loss in boiler thermal efficiency and long shutdown of boiler operation for repair.

International Journal of Energy Applications and Technologies, Year 2025, Vol. 11, No. 1, pp. 1-12

Technical literature review, pertaining to furnace exit gas temperature monitoring and evaluation of thermal performance of industrial boilers was carried out. The following is the brief description of the work that has been carried out in this field.

Basu, Kefa and Jestin explained about the designing of furnace exit gas temperature of large scale oil boiler in the range of 1350 °C - 1400 °C [1]. Yan Xie, Xin Liu, Chaoqum Zhang, Jun Zhao and Heyang Wang [2] discussed on boiler fireside Computational Fluid Dynamics (CFD) model coupled with steam cycle for the prediction of steam characteristic at different operating conditions of boiler. Sadik Kakac [3] described furnace designing and calculating of the furnace exit gas temperature by considering the various aspects like characteristics of fuel, flame and combustion, burner arrangement, characteristics of furnace heating surface area etc.

Donatello Annaratone [4] discussed about heat transfer mechanism in water and smoke tube boilers as well. Heyang Wang, Chaoqum Zhang and Xin Liu Heyang Wang, Chaoqum Zhang and Xin Liu [5] applied Computational Fluid Dynamics (CFD) technique for the evaluation of heat distribution of boiler heat transfer surfaces.

Pawel Madejski, Piotr Zymelka [6] described and showed results of boiler efficiency calculated at different operating loads with different coal fuels by indirect method and estimated terminal conditions of steam. Cristobal Cortes and Luis I. Diez [7] also discussed about the short coming and inherent difficulties of the calculation and interpretation of the process parameters of boiler. Kumar Rayaprolu [8] explained about optimum furnace exit gas temperature and gives recommendation for maintaining it 100°C below to the Initial Ash Deformation Temperature (IADT) of the fuel as margin of safety against fouling. AB. Gill [9] and Rodney R Gray [10] also discussed about thermal evaluation of boiler steam and water cycle. ASME PTC 4.4 [11] and P. Chattopadhyay [12] presented the enthalpies of hot combustion gases at elevated temperature in detail.

Richard I. Levin and David S. Rubin [13] illustrated the application of statistical methods for solving real world problems. Charles P. Bonini., Warren H. Hausman and Harold Bierman Jr. [14] discussed the application of quantitative analysis for using statistical techniques.

T. F. Wall, S. P. Bhattacharya, D. K. Zhang, R.P. Gupta and X. HE [15] and A. Ots [16] discussed the properties of ash and thermal effects of ash deposits in furnaces and other heat transfer areas of the boiler. Yanguo Zhang, Qinghai Li and Hui Zhou [17] discussed about the methods of heat transfer calculation in furnace. Youngio Kang, Joonho Lee and Kazuki Morita [18] described measurement techniques for thermal conductivity of molten slag. Qiang Li, Qian Wang, Jiansheng Zhang, Weiliang Wang and Jizhen Liu [19] discussed on transition temperature and thermal conduction behavior of slag in gasification process. V.Ganapathy [20] discussed about the radiative heat transfer method and assumptions for the estimation of furnace gas exit temperature. George H. Babcock [21] discussed boiler heat transfer and furnace slagging matters. Arafat A, Bhuiyan and Jamal Naser [22] discussed the method of quantifying furnace slagging in industrial furnaces. Nor Jauhara Sophia and Hasri Hasini [23] discussed about development of coal slagging assessment based on historical data of characteristics of coal used at plant.

The boiler under study is a compact box type utility boiler and designed to run steam turbine of 323 MWe. On account of loss of turbine rated output and efficiency due to turbine aging effects, the subject boiler was not able to supply enough steam to the turbine to get its rated output on demand especially in hot ambient conditions. The available extra margins of boiler capacity were exhausted and operation of steam cycle under such conditions was not economical. Therefore, in-order to bring back the steam cycle to its economical state and even further improve, steam turbine retrofit activity was carried out with improved version of high and intermediate pressure turbines (Dense pack) along-with re-sizing of boiler heat transfer section. In-order to monitor the impact of turbine efficiency improvement on boiler fuel and combustion after aforesaid changes, furnace exit gas temperature sensors were installed in the area close to the vicinity of boiler secondary super heater (refer Fig-1) originally the measurement facility of furnace gas exit temperature was not available at this boiler. There are two types of non-contact temperature sensors available in power industry for the measurement of FEGT, and they are called Acoustic type and Infrared type pyrometers. Acoustic pyrometer utilizes the change in the speed of sound signal generated by the sensors to determine the furnace gas temperature whereas Infrared sensor detect CO_2 of furnace combustion gas infrared energy by using filter to block all other wavelengths of infrared emission of other constituents of hot combustion gases leaving the furnace. The reported accuracy of these both types of pyrometers for the temperature range of furnace is comparable and within ± 1%. Both types of these sensors have their own merits and de-merits, however based on project consultant recommendation, Infrared sensors were installed. In some of the old boilers, contact type thermocouples are found for FEGT measurement. These thermocouples are installed near top of the furnace area. On account of limited reach and capability of measuring small area temperature, these thermocouples are only sensitive to local variations of the furnace flue gas temperature thus are not effective for the measurement of average temperature of furnace exit gas.

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Moreover, on account of direct in contact and exposure to furnace hot combustion gases stream vibration fatigue, the life expectancy of these thermocouples is also reported low.

The subject study was conducted to validate the temperature measurement of newly installed infrared sensors at furnace exit area by doing furnace heat and mass balance.

Mostly the application of furnace radiative heat transfer model has been observed in the literature review for the purpose of modeling and predicting the performance of the furnace. There are numerous parameters like emissivity of furnace wall, emissivity of burner flame, co-efficient of various factors of furnace walls like heat retention, absorption, average thermal efficiency, fouling and angular co-efficient of radiation etc. have to be assumed from the best practices or to be gathered from design literature of furnace. The access to such information is limited at plants and in industries in general, therefore in-order to develop and test furnace radiative heat transfer model, extensive trial and error exercises are required to tune the model before running in the real environment. In this study furnace heat and transfer model was used and recommended on the basis of its demonstrated accurate results and ease of its application in the evaluation of complicated areas of the power plant thermal cycle. Simulation of furnace exit gas temperature was also performed by using Excel statistical solver module in this study which has not been reported by any previous researcher to date based on literature review done so far. Estimation of Ash deposit layer thickness on furnace wall was also done as one of the important cause of increase in FEGT. Sensitivity analysis of FEGT was also performed on critical process variables of the furnace.

2. Description of Boiler Under Study

The boiler under study is a compact box type subcritical oil fired utility boiler of steam turbine of 323 MWe. The design main and reheat steam flow rate of boiler are 286 kg/sec and 248 kg/sec respectively. The design pressure and temperature of main and reheat steam are 194 bar absolute / 540°C and 51bar absolute / 540°C respectively. Figure 1, shows the process flow diagram of the working fluids of the boiler. The combustion chamber of the subject furnace is equipped with 16 steam atomized burners with opposed firing arrangement of burners at two different levels of furnace evaluation. Cold combustion air is forced to furnace combustion chamber through forced draught fans after heating at Steam Air Heater (SAH) and at Gas Air Heater (GAH). De-super heating attemperators are provided to control and maintain boiler super heaters and re-heater outlet steam temperature. Gas Recirculation Fan (GRF) is also provided to circulate part of the flue gases leaving the economizer back to the furnace chamber for better steam temperature control especially at times of boiler part load operation. The plant understudy is equipped with soot blowers for online cleaning of the boiler heat transfer surfaces above the furnace area only.

In order to monitor and control furnace exit gas temperature, two Infrared temperature sensing devices are mounted on the furnace walls opposite to the location of the burner walls in the vicinity of furnace radiant zone and close to boiler Secondary Super Heater (SSH); refer Figure 1 and Figure 2. The subject oil fired boiler is designed to operate up to 1370°C of FEGT safely, this design parameter is comparable to other large scale oil fired utility boiler having operating temperature range of FEGT 1350 °C - 1400 °C [1].

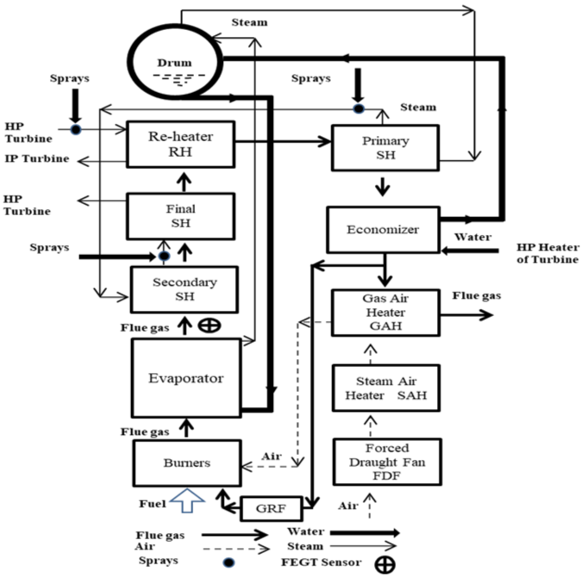

Fig.1. Process flow diagram of boiler

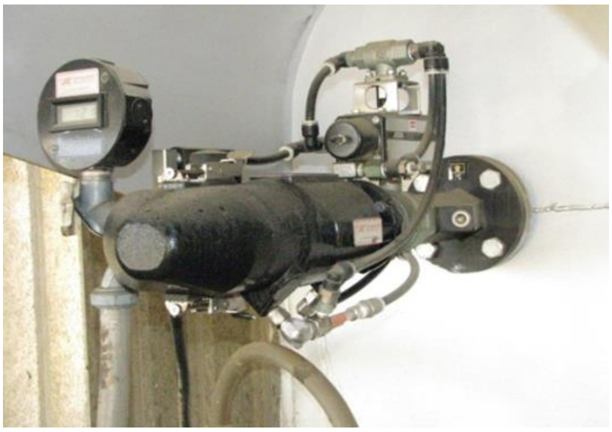

Fig. 2. Infrared temperature sensing device for furnace exit gas temperature (FEGT) measurement

2.1. Furnace thermodynamic heat and mass balance model

The subject model is based on the concept of heat and mass balance of furnace working fluids with the aim to calculate the Furnace Exit Gas Temperature (FEGT). The following are the governing equations used for the calculation of the furnace exit gas temperature [4, 9, and 10].

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$$Q_{Total} = Q_{Evap} + \dot{m}_g \left(h_{fur,\, g\, exit} - h_{fur,\, g\, ref} \right) + Q_{Rad,\, fur} \tag{1}$$

$$Q_{Evap} = \dot{m}_{fw,\, Eco,o} \left(h_{sat,\, steam\, drum} - h_{fw,\, Eco,\, o} \right) \tag{2}$$

$$Q_{Total} = Q_{fuel} + Q_{hot\, air} + Q_{atom\, steam} + Q_{GRF} \tag{3}$$

$$Q_{fuel} = \dot{m}_{RFO\ fuel,\ LHV} + \dot{m}fuel\ h_{Cp\ fuel} \left(t_{fuel} - t_{fuel,\ ref} \right) \tag{4}$$

$$Q_{hot\ air} = \dot{m}air\, C_{P,\, air} \left(t_{hot\ air} - t_{air,\ ref} \right) \tag{5}$$

$$Q_{auto\ steam} = \dot{m}_{auto\ steam} \left(h_{auto\ steam} - h_{make\ up\ water,\ ref} \right) \tag{6}$$

$$Q_{GRF,\, g} = \dot{m}_{GRF,\, g} \left(h_{GRF,\, g} - h_{GRF,\, g\, ref} \right) \tag{7}$$

$$Q_{Rad,\, fur} = 0.2\,\%\, Q_{Total} \tag{8}$$

$$\dot{m}_{air'} = 4.31 \times \left[\left(\frac{8}{3} \times \frac{C_{fuel}\,\%}{100} \right) \right] + 8 \times \left[\left(\frac{H_{2\, fuel}\,\%}{100} - \frac{O_{2\, fuel}\,\%}{100 \times 8} \right) + \frac{S_{fuel}\,\%}{100} \right] \tag{9}$$

$$\dot{m}_{air} = \dot{m}_{air'} \times \left[1 + \left(\frac{ECo.\, outlet\ O_2\ \%}{21\text{-}ECo.\, outlet\ O_2\ \%} \right) \right] \tag{10}$$

$$\dot{m}_g = \dot{m}_{fuel} + \dot{m}_{air} + \dot{m}_{auto\ steam} + \dot{m}_{GRF,\, g} \tag{11}$$

$$h_g = \sum \dot{m}_i \times h_i \tag{12}$$

$$Q_{Total} - Q_{Evap} - Q_{Rad,\, fur} = \dot{m}_g \left(h_{fur,\ g\, exit} - h_{fur,\ g\, ref} \right) \tag{13}$$

Equations (1) and (3) are the governing equations of the heat and mass balance of furnace chamber whereas equations (4), (5), (6), and (7) are used to get the Q_{Total} supplied to the furnace. After obtaining Q_{Total} from eq. (3), furnace radiation loss $Q_{Rad,fur}$ is calculated by using eq. (8). Reference to the American Boiler Manufacturers Association's (ABMA) standard guidelines for radiation loss estimation [8], 0.2% of total heat supplied to the boiler provides a good estimation of boiler heating surface radiation loss for the size of boiler under study. Equations (9) and (10) are used for calculating combustion air mass in view of fuel combustible elements presence and excess air supplied in the combustion chamber. Equation (2) presents the heat absorption of furnace water by evaporation. Equation (11) is used to calculate the total mass flow of flue gases in the boiler. Referring to eq. (12), h_g is the enthalpy of furnace gas which is the sum of product of mass fraction of each elements of the furnace gas to its respective enthalpy at the relevant temperature. In order to perform computer iterations for the estimation of furnace exit gas temperature to balance out both sides of the eq. (13), polynomial equation was developed to calculate furnace gas enthalpy as a function of furnace exit gas temperature. Table 1 shows polynomial equation constants of enthalpy of the constituents of furnace combustion gas for the temperature range of 15°C to 2000°C whereas Table 2 shows the polynomial equation constants derived for furnace gas enthalpy (h_g), based on mass fraction (71.696% N_2, 1.413% O_2, 19.446% CO_2, 0.347% SO_2 and 7.098% H_2O) of furnace combustion gas constitutes as a function of furnace exit gas temperature ($t_{fur,\ g\ exit}$) for the temperature range of 15° to 2000°C [11, 12]. Excel software regression module was used for the development of aforesaid polynomial equation of 3^{th} order.

Table 3 shows the summary report of Excel regression module and demonstrates the furnace combustion gas enthalpy 5^{th} order polynomial equation coefficients and quality of data fit i.e. R^2=1.

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Table 1. Polynomial equation constants of furnace gas constituents enthalpy (kJ/kg)

Constituents of Combustion Gas	Constant	at^1	bt^2	ct^3
N_2	-7.139E-01	1.024E+00	8.691E-05	6.690E-09
O_2	-4.572E+00	9.186E-01	1.575E-04	-3.668E-08
CO_2	3.945E-01	8.414E-01	4.042E-04	-1.180E-07
SO_2	-3.138E-02	6.204E-01	2.519E-04	-8.226E-08
H_2O	-1.584E+00	1.839E+00	2.981E-04	5.368E-09

Table 2. Polynomial equation constants for furnace gas enthalpy (kJ/kg)

Constant	at^1	bt^2	ct^3	dt^2	et^3
-6.123E-01	1.043E+00	1.652E-04	-1.856E-08	8.576E-25	-1.310E-28

Table 3. Summary report of regression analysis of polynomial equation of furnace gas enthalpy (kJ/kg) for the temperature range of 15°C to 2000°C

Regression Statistics	
Multiple R	1.0000000
R Square	1.0000000
Adjusted R Square	1.0000000
Standard Error	2.874E-13
Observations	28

ANOVA

	df	SS	MS	F	Significance F
Regression	5	3.115E+07	6.230E+06	7.542E+31	0.000E+00
Residual	22	1.817E-24	8.260E-26		
Total	27	3.115E+07			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-6.123E-01	1.843E-13	-3.321E+12	3.337E-262	-6.123E-01	-6.123E-01
X Variable 1	1.043E+00	1.979E-15	5.272E+14	0.000E+00	1.043E+00	1.043E+00
X Variable 2	1.652E-04	5.441E-18	3.036E+13	2.416E-283	1.652E-04	1.652E-04
X Variable 3	-1.856E-08	5.742E-21	-3.233E+12	6.036E-262	-1.856E-08	-1.856E-08
X Variable 4	8.573E-25	2.571E-24	3.334E-01	7.420E-01	-4.475E-24	6.190E-24
X Variable 5	-1.310E-28	4.109E-28	-3.187E-01	7.529E-01	-9.832E-28	7.212E-28

2.2. Simulation of Furnace exit gas temperature

Fifteen variables were selected (refer figure 1) to model the furnace exit gas temperature that have significant direct and indirect influence on furnace duty, combustion and on furnace exit gas temperature in accordance with the sequence of boiler operation. When the boiler operator set the target steam turbine generator electrical load then the fuel, combustion air and feed water flow controllers adjust their output to meet the target load demand and subsequently send the signals to the respective field equipments and other controllers to get the operator set target load. The process parameters which indirectly significantly reflect these changes were added in the list of variables for this study like economizer outlet excess oxygen, feed water temperature at economizer outlet, atomizing steam flow to burners, Gas circulating fan damper opening position, burner count, flue gas smoke density, inlet combustion air temperature, gas circulation fan outlet temperature. Some other factors like boiler blow down valve opening, super heater and re-heater spray flows were also included which have indirect significant impact of boiler feed water flow for this simulation study of furnace exit gas temperature. Reference to eq. (14) the list of all the fifteen variables are given below. Calorific value of Residual Furnace Oil (RFO) is not included in the list of variables as RFO has been supplied to the Plant under Fuel Supply Agreement (FSA) with minimal allowed variation in the fuel specifications.

$$FGET = \varphi\ (x_1, x_2, x_3, x_4, x_5 ----- x_{15}) \quad (14)$$

The following is the list of fifteen selected variables.

1. Steam turbine generator electrical load (MWe)
2. Fuel flow (metric ton /hr)
3. Feed water flow (metric ton /hr)
4. Combustion air flow (%)
5. Economizer outlet excess oxygen (%)
6. Feed water temperature at Economizer outlet (°C)'
7. Atomizing steam flow to burners (metric ton /hr)
8. Gas Circulation Fan damper opening (%)
9. Burners count (Numbers)
10. Flue gas Smoke Density, SD (%)
11. Boiler blow down valve opening (%)
12. Furnace inlet combustion air temperature (°C)
13. Gas Circulation Fan outlet temperature (°C)
14. Super heater spray flow (metric ton /hr)
15. Re-heater spray flow (metric ton /hr)

For the purpose of simulation of furnace exit gas temperature the aforesaid variables data was collected at generator different electrical loads starting from 20% minimum stable electrical load to maximum 100% with 10% incremental change. One-hour stabilization period was set for the thermal process parameters upon reaching each incremental change in the steam turbine generator load. Boiler data collection was carried out at 60 sec interval per sample from Station Plant Information (PI) server connected to Plant Distributed Control System (DCS) and average out for one hour period for performing the simulation of boiler furnace gas exit temperature.

Excel Solver optimizing module was used for the prediction of furnace gas exit temperature due to its flexibility of dealing integer variables and nonlinear function, as well as linear ones [13,14] first time in this study instead of traditionally applied techniques of data analysis.

In Excel Solver module, the difference of measured and calculated furnace exit gas temperature i.e. $\Delta T = (FEGT_{meas} - FEGT_{cal)}$ was set as target for the minimization by changing the coefficient of all fifteen variables (eq.14) of the objection function. Table 4 presents coefficient of variables of the equation (14) developed for predicting of the furnace exit gas temperature by Excel Solver module. The coefficient of variables of eq.14 shows the ±Δ change in the furnace exit gas temperature on account of per unit change in the value of respective variable. Table 5 shows the statistical analysis and quality of fitness of predicted furnace gas exit temperature based on Solver output in comparison to the measured data of furnace flue gas exit temperature. The correlation coefficient of the measured and predicated data of FEGT is nearly unity. However, further discussion on simulated model has been made in section 3.0.

Table 4. Co-efficient of variables of the equation (14) developed for predicting the furnace exit gas temperature by Excel Solver module

x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	Const:
Gen. Load	Fuel flow	FW flow	Comb air	ECO outlet Oxy.	ECO FW Outlet temp	Atom steam flow	GRF Damper Open	Burners Count	Smoke Density	BBD v/v Open	Comb air Temp	GRF Outlet Temp	SH spray	RH spray	Const:
1.862	69.091	-1.911	-43.363	37.884	1.828	-20.745	-4.712	18.963	-3..08	0.283	0.866	-1.358	0.076	1.057	1000.098

Table 5. Statistical analysis of solver output of furnace flue gas temperature (FFGT)

Statistical Observations	Measured (FEGT)	Predicted (FEGT) - Slover
Data Range (Maximun - Minimum)	375.626	375.028
Mean	1050.703	1050.703
Median	1077.815	1077.592
Standard Deviation	147.915	147.889
Standard Error of mean (SEM)	33.0747	33.0690
Cofidence Level (95%)	69.2262	69.2141
Correlation Coefficient	0.9998665	

2.3. Sensitivity analysis of furnace exit gas temperature

Furnace heat and mass balance model was used for performing sensitivity analysis of furnace exit gas temperature, refer to figure 3. Five percent variation (increase /decrease) was given to the following variables in view of their importance as discussed in section 2.2.

Five percent increase or decrease in fuel mass flow can increase or decrease furnace exit gas temperature up to ±

International Journal of Energy Applications and Technologies, Year 2025, Vol. 11, No. 1, pp. 1-12

47°C and on the other hand five percent decrease or increase in feed water mass flow to boiler can increase or decrease the furnace exit gas temperature up to ± 42°C. The change in boiler feed water flow is almost inversely proportional with respect to the change in boiler fuel flow. This is due to the fact that decrease in boiler feed water flow, will reduce the furnace duty. The reduction in furnace duty will increase the furnace exit gas temperature on account of less exchange of heat to furnace circulating feed water as the fuel flow to the boiler is unchanged. Similarly, the five percent decrease or increase in air mass flow to boiler can increase or decrease the furnace exit gas temperature up to ± 36°C. This relationship is also inversely proportional to each other. This is due to fact that the reduction in air supply quantity of the furnace will reduce the available excess air which is required to ensure complete boiler combustion and cooling down of furnace gases before exit of furnace. Therefore, the reduction in excess air quantity will lead to increase FEGT. The impact of variation in fuel heating value on furnace exit gas temperature was also analyzed to get the realization of its impact in comparison with other operational parameters of the furnace; ± 5% increase or decrease in fuel Lower Heating Value (LHV) can change the furnace exit gas temperature up to ± 89°C which is a significant change, however as discussed in section 2.2, such variation of LHV is not expected due to shipment of oil supply under Fuel Supply Agreement (FSA). Nonetheless, this information provides the insight to the plant operators to have the strict compliance of this fuel parameter according to FSA fuel specification.

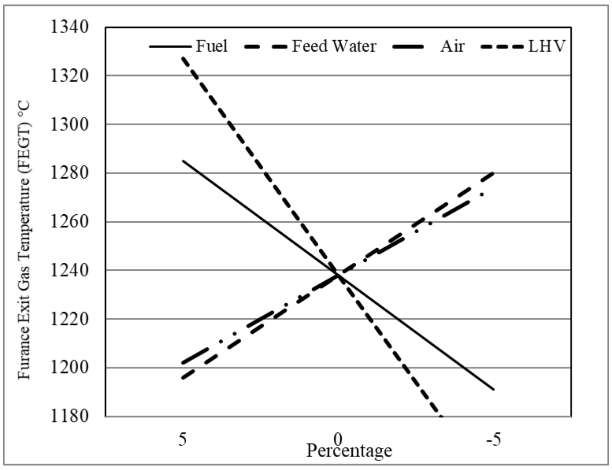

Fig. 3. Sensitivity analysis of furnace exit gas temperature

The purpose of performing sensitivity analysis of furnace exit gas temperature (a new addition of important operational factor in the boiler combustion process) is to provide a better understanding to the boiler operators about the anticipated change in FEGT on account of change in the important furnace combustion process factors like fuel, air, feed water flow and fuel lower heating value. Any abrupt change in FEGT will require a thorough investigation in-order to safeguard the furnace and boiler from accelerated slagging and fouling by performing operational checks and controls. The immediate impact of increase in FEGT can be seen in increasing trend of de-superheating sprays of the boiler. The increase in de-superheating sprays of the boiler have negative impact on steam thermal cycle efficiency (refer section 3).

2.4 Modeling of furnace slagging and fouling impact on FEGT

The modeling of incremental increase in FEGT on account of furnace slagging and fouling was performed [15] by applying following relationship as given in equation (15). Furnace clean and dirty condition was compared to model furnace slagging and fouling impact on FEGT by keeping the heat input to the furnace as constant in both the conditions. The decrease in heat absorbed by furnace evaporator (ΔQ) on account of slagging and fouling thickness (Δ*x*) on furnace walls was modeled against increase in FEGT. Referring to table 6, if the FEGT of the clean furnace increases by 149°C due to furnace fireside fouling and slagging alone then the corresponding thickness (Δ*x*) of the deposits on furnace surface having thermal conductivity of λ=0.55 W/m °k [16-19] can be estimated as 15 mm. Figure 4 and 5 illustrates clean and dirty conditions of the furnace understudy. It is observed that the area of furnace adjacent to oil burners have relatively hard and thick layer of slag as compared to the furnace side walls. One of the obvious reasons of hard and thick slag is due to high heat flux in the burner area walls. However, some operational issues like poor atomization and chocking of oil burners, improper burner air distribution and burner flame curl back incidences are those factors which further aggravate the slag formation in aforesaid burner area of the furnace.

$$\Delta x = \frac{\lambda A \Delta t}{\Delta Q} \qquad (15)$$

$$t_{wall} = \left[\frac{t_{water,Eco,o} + t_{water,boiler\ drum}}{2}\right] + 100 \qquad (16)$$

Fig. 4. Dirty condition of the furnace understudy

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Table 6. Clean vs Dirty boiler conditions - heat and mass balance model output

Description	Units	Rated Boiler Load (Clean Furnace)	Rated Boiler Load (Dirty Furnace)	Remarks
Heat Input to the furnace:				
Fuel	MJ/Sec	753.825	753.825	
Fuel sensible heat	MJ/Sec	3.547	3.547	
Hot combustion air	MJ/Sec	88.539	88.539	
Atomizing steam	MJ/Sec	2.458	2.458	
Gas recirculation fan	MJ/Sec	6.757	6.757	
Total heat input to the furnace	MJ/Sec	855.127	855.127	
Furnace radiation heat loss	MJ/Sec	1.710	1.710	
Net heat available in the furnace	MJ/Sec	853.420	853.420	
Heat absorbed by furnace evaporator	MJ/Sec	392.608	329.790	Δ Q = 62.820
Heat leaving the furnace	MJ/Sec	460.808	523.630	
Δt = Difference of Furnace deposit layer temp. and Furnace metal tube temp (T_{wall}) Eq. (16)	°C	0	724	Δt =724°C T_{wall} = (275+359)/2+100 =417°C
Furnace Exit Gas Temperature (FEGT)	°C	1238	1387	Refer Eq. (13) Diff:=149 °C
$\Delta x = \frac{\lambda A \Delta t}{\Delta Q}$ Eq. (15)	mm	0.00	15.15	Δt =724 °C λ= 0.55 W/m °K A = 2390 m^2

Fig.5. Clean condition of the furnace understudy

3. Results and Discussion

Thermodynamic model and simulation model values of furnace exit gas temperature have been presented in table 7 along-with measured values of FEGT recorded by Infrared sensors at minimum and maximum loading conditions of the furnace for the purpose of comparison. Referring to figure 2, these infrared temperature sensors are non-contact sensors which are designed to detect only CO_2 gas infrared energy by using filter to block all other wavelengths of infrared emission of other constituents of hot combustion gases leaving the furnace. The accuracy of these newly purchased accredited laboratory calibrated sensors for the temperature measuring range of 120°C to 1650°C is ± 1%. The subject Infra-red sensor provides rolling average of temperature readings based on the principle of First-In-First-Out of data with temperature readout facility of 0.1 second to 55 seconds. These sensors also have the facility to hold peak temperature. The response time of these sensors is 100 milliseconds.

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Table 7. Measured and Calculated FEGT by Heat and Mass balance and Simulation model

Description	Furnace exit gas temperature °C			
	Min. Boiler Load (70MWe)	**Rated Boiler Load (323MWe)**	**Measured – Calculated temperature Min. Boiler Load**	**Measured – Calculated temperature Rated Boiler Load**
Thermodynamic Heat and Mass Balance Model (Calculated)	835	1238	14	-18
Simulation Model, Excel Statistical Solver module (Calculated)	853	1218	-4	2
Infrared Instrument (Measured)	849	1220		

The measured and calculated furnace exit gas temperatures found in close agreement. Referring to the table 7, the difference between measured and calculated values of furnace exit temperature of heat and mass balance model is within ± 20°C, whereas simulation model results are within ± 5°C. The reason of less difference between predicated temperature of furnace exit gas by simulation model & measured furnace exit gas temperature is due to good statistical correlation of fifteen (15) selected boiler and turbine operational parameters which have direct and indirect impact on furnace exit gas temperature of boiler as explained in detail in section 2.2. The difference between measured and calculated values of furnace exit temperature of heat and mass balance model which is within ± 20°C can be further reduced by improving measuring accuracy of mass flow of following critical boiler parameters like feed water, air flow and fuel flow. In order to see the impact of these critical parameters on FEGT, sensitivity analyses were performed and discussed in detailed in section 2.3. Figure 6 illustrates the good co-relation of stimulated and measured values of furnace exit gas temperature (°C) with respect to various operating conditions of steam turbine generator electrical output (MWe) whereas figure 7 shows the difference between measured and calculated FEGT by simulation model with respect to various operating conditions of steam turbine generator electrical output (MWe). As described the section 2.2, for the purpose of simulation of furnace exit gas temperature, the incremental change in generator load was set 10% starting from 20% minimum stable electrical load to 100% generator load. At 50% incremental generator load due to unexpected system grid disturbance the holding point at 50% load was skipped. Upon achieving required data at 60% generator load an addition holding point at 65% of generator load was added in the scheme of data collection (refer fig.6). Numerous operational factors like magnitude of fouling and slagging of furnace heat transfer surfaces, calibration issues of plant instruments, fuel quality related matters etc. [20,21] FEGT can go significantly high. In order to safeguard the boiler operation, two alarm limits are introduced for FEGT i.e., one at 1350 °C and other at1450°C in view of boiler and turbine design steam operating conditions.

Tracking of the measured FEGT has been done usually on plants by Operator Information Screen (OIS). Tracking of measured FEGT alone is not enough unless an independent back ground calculation of FEGT by heat and mass balance and by simulation modal should also be done simultaneously for the purpose of performing FEGT online validation and simulation.

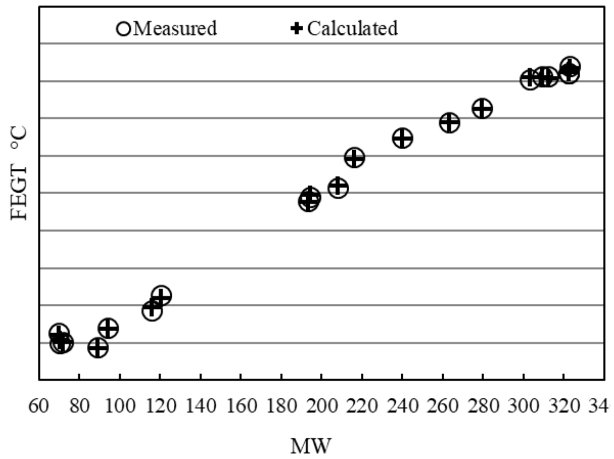

Fig. 6. Simulated and measured furnace exit gas temperature at different turbine loads

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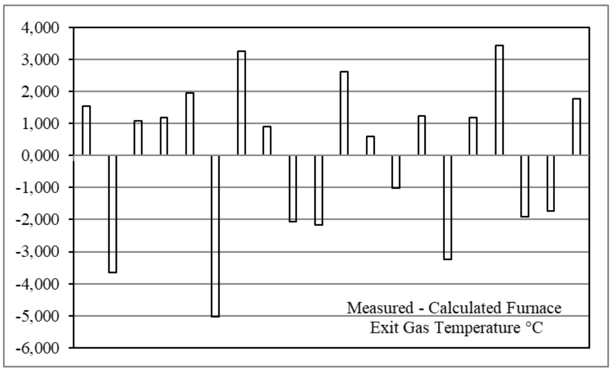

Fig. 7. Simulated and measured furnace exit gas temperature difference (± 5°C) at different turbine loads (refer Fig.6)

The outcome of furnace FEGT sensitivity analysis was discussed in detail in section 2.3, four significant variables of furnace i.e. boiler fuel flow, boiler feed water flow, boiler combustion air flow and fuel Lower Heating Value (LHV) were analyzed by varying 5 percent change in the base value of these variables.

The impact of furnace slagging and fouling on FEGT was also modeled and it was found that15 mm thick layer of deposits on furnace walls can increase the FEGT to 149°C [22,23] refer table 6.

The immediate impact of increase in FEGT can be seen in increasing trend of de-superheating sprays of the boiler. Plant archive data shows that in case of fouled boiler the delta increase in Re-heater and Super- heater de-superheating can go up to the range of 100 tons per hour. The increase in de-superheating sprays of the boiler is an efficiency loss to the plant thermal cycle. It has been estimated that cumulative effect of increase in de-superheating sprays as discussed above can increase thermal cycle heat rate to73.5 kJ/kWh which is quite significant loss. Therefore it is very important to get an understanding of the reasons of gradually increasing trend of furnace exit gas temperature over the period of boiler operation in-order to safeguard the furnace from accumulation of slag & subsequent furnace damages and to avoid plant thermal cycle efficiency losses. Figure 4 and 5 illustrates the extent of dirty fireside surfaces in comparison with the clean furnace surfaces of the boiler understudy before the installation of the Infrared sensors for the measurement of FEGT at plant.

4. Limitation of the Study and Future Proposed Area of Research

The scope of this study is limited to the matters relating to furnace heat transfer of the boiler. In-order to analyze the impact of reduction in heat transfer of the furnace and consequently increase in furnace exit gas temperature over extended period of the boiler operation, a detailed study is proposed by performing heat and mass balance of the complete boiler including boiler efficiency calculation in line with ASME Steam Generator Performance Test Code 4.1. Moreover, cost benefit analysis of boiler soot-blowing activity is also proposed in-order to optimize its cyclic operation.

5. Conclusion

Validation and simulation of Furnace Exit Gas Temperature (FGET) study was carried out and results were compared with the measured values of newly installed Infrared sensors at furnace exit of boiler of power generating steam turbine of 323 MWe. The following are the observations;

1. The ΔT between measured and calculated furnace exit gas temperature by heat and mass balance model was ± 20 °C based on furnace duty at minimum and rated load of steam turbine generator.
2. The ΔT between measured and calculated furnace exit gas temperature of fifteen (15) selected process parameters of furnace that have direct and indirect impact on furnace duty was ± 5 °C. It is pertinent to mention that Excel solver module was applied for the first time to get multivariable objective function solution for the purpose of FEGT simulation in this study.
3. The modeling of increase in FEGT with respect to the thickness of furnace slag was performed and it was calculated that 15 mm thick layer of slag on furnace surface could increase FEGT by 149°C based on furnace slag thermal conductivity (λ) equal to 0.55 W/m °K. The furnace under study is not equipped with soot-blowing facility; therefore it is important that the subject model should be run time to time for the assessment of the extent of furnace fouling and slagging, especially before boiler annual shutdown for the purpose of planning resources required for furnace cleaning activity.
4. Sensitivity analysis of FEGT was also carried out by varying ± 5% in the base value of the four significant process parameters of furnace i.e. fuel flow, feed water flow, combustion air flow and fuel Lower Heating Value (LHV). The outcomes of sensitivity analysis are as under; Fuel flow ± 47 °C, Feed water flow ± 42 °C, Combustion air ± 36 °C and LHV ± 89 °C.

   It is worth mentioning here that the increase in boiler feed water flow and combustion air flow will decrease the FGET, whereas decrease in feed water flow and combustion air flow will increase FEGT. On the contrary increase / decrease in fuel flow and fuel lower heating value will increase / decrease FEGT respectively. The increase in FEGT will increase the baseline quantity of steam boiler de-superheating sprays, which is a loss to steam thermal cycle efficiency. It is estimated that increase in de-superheating of 100 tons per hour from the baseline de-superheating sprays will deteriorate the thermal cycle heat rate to73.5 kJ/kWh, which is a quite

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significant loss. In-depth understanding of the subject sensitivity analysis of FEGT is essential for the plant operators for the purpose of root cause analysis of deviation of FEGT from its operational optimum values and to safe guard the plant from consequent losses.

5. The tracking of measured FEGT has been done on plants by Operator Information System (OIS). The tracking of FEGT alone is not adequate unless an independent back ground calculation of FEGT by running heat and mass balance and simulation models should also be done simultaneously as discussed and demonstrated in this study. This is required to understand and address any anomaly between measured and calculated and simulated furnace exit gas temperature.

Conflict of interest

There is no conflict of interest.

Nomenclature		**Subscripts**		**Acronyms**	
A	Area (m^2)	atom	Atomizing	ASME	American Society of Mechanical Engineers
C_p	Constant pressure specific heat, [kJ kg^{-1} K^{-1}]	cal	Calculated	CFB	Circulating Fluidize Bed
CO_2	Carbon dioxide [%]	Eco	Economizer	CFD	Computational Fluid Dynamics
h	Enthalpy [kJ kg^{-1}]	Evap	Evaporator	DCS	Distributed Control System
hr	Hour	Fw	Feed water	FSH	Final Super Heater
H_2O	Water [%]	fur	Furnace	FSA	Fuel Supply Agreement
LHV	Lower heating value of fuel [MJ kg^{-1}]	FEGT	Furnace gas exit temperature	GAH	Gas Air Heater
m	Meter [m]	GRF	Gas recirculation fan	HP	High Pressure
$\dot{m}$	Mass flow rate [kg sec^{-1}]	g	Gas	IP	Intermediate Pressure
MWe	Megawatt Electrical [10^6J s^{-1}]	o	Outlet	LP	Low Pressure
NO_2	Nitrogen dioxide [%]	meas	Measured	PSH	Primary Super Heater
O_2	Oxygen [%]	ref	Reference Condition [Site ambient conditions]	PI	Plant Information System
q	Heat Flux [W/m^2]	Rad	Radiation	SSH	Secondary Super Heater
SO_2	Sulphur dioxid [%]	RFO	Residual Furnace Oil		
t	Temperature [°C]	sat	Saturation		
W	Watt [J/Sec]				
x	Thickness [mm]				
Greek letters					
∑	Sum [-]				
φ	Function [-]				
λ	Thermal Conductivity [W/m °K]				
Δ	Difference [-]				

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