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Research Paper

Mathematical modeling and validation of a 320 MW tangentially fired boiler: A case study

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HIGHLIGHTS

- Detailed and robust mathematical model of 1056 t/h capacity boiler is developed.
- Air pollutants prediction is captured considering equilibrium combustion.
- Rotary regenerative air heater (Ljungström) model is validated and included.
- Inlet/outlet temperature of each part of the boiler are validated with 8.72% error.
- Averaged energy distribution in the boiler are presented and analyzed.

ARTICLE INFO

Keywords:
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Boiler
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ABSTRACT

The main step to evaluate the effect of various parameters on optimal operation conditions and pollution reduction of a boiler is to create a detailed model. In this paper, a steady state integrated model of boiler has been developed. Besides implementing main components of boiler applying thermodynamics laws, heat transfer and pressure drop correlations, following aspects have been considered: equilibrium combustion to predict flue gas composition and temperature, recirculation gas in the furnace, furnace exit gas temperature, radiation of the flue gases to the waterwall and superheaters, desuperheaters and rotary regenerative air heater (Ljungström). Heat transfer surfaces are considered as heat exchangers including direct and inter-tube radiation energy. The model was successfully applied to 320 MW tangentially fired boiler of Bandar Abbas power plant in Iran at six different loads 240, 250, 260, 270, 280 and 290 MW. Inlet/outlet temperature of working fluids for each heat transfer surfaces of the boiler are presented, compared and validated against the actual measured data from the power plant with maximum relative error of 8.72%. Effect of each heat transfer surfaces of boiler on its efficiency is presented and analyzed by averaged energy distribution in the boiler.

1. Introduction

The energy required to generate electricity in fossil power plants is achieved by combustion of the fuel, and the operation of fossil power plants does entail the release of harmful pollutants and greenhouse gases to the environment [1]. Despite renewable energy growth, fossil fuels will remain dominant energy source for next 20 years [2], therefore improving the performance of boiler as the frontline of energy conversion can have a significant impact on reducing these noxious gases. Create a model to predict boiler behavior in a wide range of loads and assessing different scenarios is an essential step in performance optimization [3,4].

A good model should consist of various phenomena that occur in the boiler, such as combustion in the furnace, diversity of the flue gas composition include air pollutions, hot flue gas absorptivity and emissivity, various heat transfer modes, pressure drop and phase change.

In the last decade, many researchers focused on CFD (Computational Fluid Dynamics) simulation of boiler and its components especially combustion in the furnace and heat transfer surfaces. For example, Modlinski [5] presented three dimensional numerical model of utility boiler tangentially-fired furnace retrofitted with swirl burners and showed how the flow, combustion performance and heat transfer in the furnace are affected by burners. Choi and Kim [6] used CFD codes to investigate the combustion and NO_x emissions in a 500 MW tangentially fired pulverized-coal boiler. Madejski et al. [7] developed a numerical three dimensional model of a steam superheater

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Nomenclature

Abbreviation

A	surface area (m^2)
A_c	cross-sectional area (m^2)
A_r	total surface area of the regenerator matrix exposed to the fluid (m^2)
$A^{'}, B^{'}$	experimental coefficients
Bo	Boltzman number
C, C_p	specific heat capacity (kJ/kg°K)
C_1, C_2, C_3	correction factor
D	diameter of tubes (m)
d_{eq}	equivalent diameter (m)
F	effective surface area of the waterwall (m^2)
f	friction factor
F_c	LMTD correction factor
F_{ij}	view factor from i to j
F_s	effectiveness factor based on areas
H	height (m)
h	specific enthalpy (kJ/kg); convection heat transfer coefficient (W/m^2°K)
$h_{c,g}$	convection heat transfer coefficient of flue gas side (W/m^2°K)
h_r	basic radiation heat transfer coefficient (W/m^2°K)
$h_{r,g}$	inter-tube radiation heat transfer coefficient (W/m^2°K)
k	thermal conductivity (W/m°K)
k_f	fuel factor
K_p	equilibrium constant
L	tube length (m)
L_c	corrected fin length (m)
L_{fin}	fin length (m)
L_P	longitudinal pitch
L_r	length of the regenerator (m)
M	temperature field
MM	molar mass (kg/kmol)
$\dot{m}$	mass flow rate (kg/s)
n	mole
N_P	number of passes
N_R	number of tube rows
N_T	number of tubes
P	pressure (Pa)
P_{fin}	perimeter of fins (m)
Pr	Prandtl number
ΔP	pressure drop (Pa)
$\dot{Q}$	heat transfer rate (W)
Re	Reynolds number
S	distance between the tubes' axes (m)
T	temperature (°C)
t	thickness of the fins (m); time (s)
t_B	duration of hot-to-cold or cold-to-hot blow process
T_P	transverse pitch
ΔT	temperature difference (°K)
U	overall heat transfer coefficient (W/m^2°K)
v	velocity (m/s)
V_r	volume of regenerator material (m^3)
$V\bar{C}_p$	average specific heat (kJ/kg°K)
x	mass fraction; distance in the flow direction measured from the hot inlet (m)
X_r	relative position of the highest temperature zone in the furnace
ΔX	correction factor
y	mole fraction

Subscripts

f	fluid
fl	flame
fu	furnace
$form$	formation
g	flue gas
in	inlet; inside
$LMTD$	logarithmic mean temperature difference
out	outlet; outside
$prod$	product
r	regenerator
Rad	radiation
$react$	reactant
ref	reference
sh	superheater
std	standard
th	theoretical
w	water/steam
ww	waterwall

Greek letters

α	absorptivity
ε	emissivity
η_{fin}	fin efficiency
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant (W/m^2Â°K^4)
ϕ	coefficient of heat retention
ψ	thermal efficiency coefficient
ω	rotational speed (rpm)

using control volume based on finite element method to determine the tube wall temperature, steam temperature and pressure distributions. Maakala et al. [8] presented a detailed, three dimensional CFD modeling of heat transfer and fluid flow in a full superheater region of recovery boiler. Xu et al. [9] developed a comprehensive CFD combustion model for large-scale supercritical circulating fluidized bed (CFB) boilers and was applied in a simulation of a 350 MW supercritical CFB boiler.

On the other hand, one dimensional mathematical modeling is an efficient and economical method to investigate and calculate the energy transfer and fluids temperature in the boiler [10,11]. Pan et al. [12] developed a mathematical model for predicting mass flux distribution and metal temperature in the vertical water wall based on the mass, momentum and energy conservation equations and validated with the power plant data. Kim et al. [13,14] developed a simplified mathematical model of CFB boiler as a system of heat exchanger blocks under various loads. Validation has been carried out by comparing calculated results with experimental data of a pilot-scale CFB. Tzolakis et al. [15,16] carried out the one dimensional mathematical simulation of a 300 MW lignite-fired power boiler in gPROMS software. Also, the efficiency of the plant at full load was optimized, using the turbine stages' mass flow rate extractions and the fuel consumption. Chandrasekharan et al. [17] presented a review of modeling, identification and control of coal-fired boilers in a thermal power plant. They showed modeling of the plant is essential to design better power plants in response to meet the growing demand for power worldwide. A mathematical model of a plate fin and tubular cross-flow heat exchangers with application to automatic control of the liquid outlet temperature was developed and validated experimentally by Taler [18]. A dynamic mathematical model suitable for simulation of fast cut back of coal-fired