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Numerical model of a steam superheater with a complex shape of the tube cross section using Control Volume based Finite Element Method

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ABSTRACT

In modern utility boilers, characterized by high values of steam pressure and temperature, the individual superheater stages and also the individual passes are made of different low alloy steel grades. The use of tubes having a complex shape of cross section allows the building of the platen with smooth side surfaces, which are arranged in the upper part of the combustion chamber. This avoids the erosion of the superheater tubes and deposition of slag and ash in the spaces between adjacent tubes. The superheaters of this type are widely used in CFB boilers. To select the appropriate steel for each pass and each stage, the maximum wall temperature of tube need to be determined. Steam and tube wall temperature were computed in the superheater using a method proposed in the paper and compared with the results obtained by CFD simulation using Star-CCM+ software. The method presented in the paper can be easily applied to the modeling of flow and thermal processes in superheaters with complicated flow arrangements which usually are found in steam boilers. The advantage of the proposed method is a short computing time in comparison with detailed and complex 3D models. Using the methodology developed in the article, time needed to obtain final results at steady-state conditions can be lower even dozen times in comparison to CFD calculations. The proposed calculation method can be used in the design of modern subcritical and supercritical boilers, in which the temperature of the live steam is very high. Very careful and precise calculations of steam and tube walls temperature along the steam flow path will avoid the overheating of the tube material.

1. Introduction

Boiler superheaters are high-temperature heat exchangers, which are often subject to failures. The reasons for failures and damages of superheater elements are the difficulties of proper design, taking into account the actual and changing operation conditions. The costs of superheater tube replacement are very high due to the high prices of steel alloys which are used for producing superheaters. In view of the great importance of proper design as well as proper operation of steam superheaters, a lot of attention is devoted to mathematical modeling. In addition to the knowledge about the range of correct and safe operating conditions, also, the efficient automatic temperature control of superheated steam is an important factor in lengthening their lifetime.

Many scientific articles in the field of mathematical modeling and automatic control of temperature in the steam superheaters have been published over the last 30 years. Analytical and numerical methods are used for mathematical modeling of heat exchangers. Al-Nimr et al. [1] modeled dynamic behavior of packed bed energy storage system. The model developed in the paper is based on two coupled partial differential equations that were solved exactly. Thermal performance of the cooling tower was studied by Al-Nimr [2] to obtain a closed form solution for the temperatures of the water and air stream. Madejski and Taler [3] carried out a CFD (Computational Fluid Dynamics) and structural analysis of the superheater located in the combustion chamber of the CFB (Circulating Fluidized Bed) boiler. Numerical modeling and control of plate fin and tube heat exchangers was studied in [4].

Lorente et al. [5] explored the possibility of maximizing the power of steam turbine power plant by optimal configuration the superheater and reheater stages in the boiler. A similar problem was solved by Feng et al. [6]. They both showed that the optimization of heat exchangers arrangement of heat recovery steam generators (HRSG) was of great importance for waste heat recovery. Taler et al. [7] indicated the need to control the temperature of

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Nomenclature

Nu	Nusselt number
R_a	absolute surface roughness (m)
Re	Reynolds number, $Re = w_1 d_{in}/\nu$
Pr	Prandtl number, $Pr = c_p \mu / k$
N	number of control volumes on the tube length
L_s	total tube length in one pass (m)
A_1	cross section area of the duct (m^2)
CVFEM	control volume based finite element method
c_w	specific heat of superheater tube material (kJ/kg K)
c_p	specific heat at constant pressure (kJ/kg K)
d	omega tube width (thickness of the platen superheater) (Fig. 2b) (m)
d_h	hydraulic diameter of the duct (m)
d_{in}	inner tube diameter (m)
f_1	steam pressure at the inlet of the superheater (Pa)
f_2	steam temperature at the inlet of the superheater (°C)
g	tube thickness in a horizontal plane passing through the tube axis (Fig. 2b) (m)
g	gravitational acceleration (m/s^2)
h_1	heat transfer coefficient from superheater wall to steam (W/m^2 K)
h_2	heat transfer coefficient from flue gas to superheater wall (W/m^2 K)
k	thermal conductivity of superheater material (W/m K)
p_1	steam pressure (Pa)
r_{in}	inner radius of the tube (m)
s	curvilinear coordinate (m)
$\dot{q}$	heat flux (W/m^2)
T_f	fluid temperature (°C)
T_1	steam temperature (°C)
T_2	flue gas temperature (°C)
T_w	tube wall temperature (°C)
U_{in}	the perimeter of the tube inner surface (m)
w_1	steam velocity (m/s)
x, y, z	Cartesian coordinates (m)
n	normal direction (m)

Greek symbols

β	linear thermal expansion coefficient (1/K)
Γ_{in}	duct inner surface
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ξ	friction factor
ρ	density (kg/m^3)
φ	inclination angle of the tube in relation to the horizontal plane

Subscripts

1	steam
i	node number
w	wall

the superheater tubes during start-up of the boiler with the maximum allowable rates of the steam temperature changes. A detailed thermo-mechanical analysis of the superheater tubes makes it possible to identify the cause of premature high-temperature failures and aids greatly in the changes in tubing arrangement and improving start-up technology. Convective heat transfer in an attemperator desuperheater was simulated using CFD modeling by Kouhikamali et al. [8]. Steam temperatures in large capacity boilers of modern power units are maintained closely around the design value by injecting water into the steam to ensure safe and efficient operation of the power unit. An optimum control strategy for minimization of exergy destruction in boiler superheater was proposed Ray et al. [9]. Novel feedforward-feedback control system for steam superheaters was developed by Kim et al. [10]. A numerical study using superheater simulator indicated that the proposed system has an advantage over the existing cascade PID controllers.

Many experimental studies were also conducted to explain the causes of ash fouling of superheater surfaces, and to find the reasons for their premature failure. The build-up of scale deposits on the inner surfaces of the tubes are the cause of overheating tube material. Ash fouling of outer surfaces of the tubes is, in turn, cause of accelerated external corrosion of the tube and lowers the efficiency of the boiler. Vessakosol and Charoensuk [11] studied the effect of ash fouling on heat transfer around a cylinder in cross flow numerically. A conjugate heat transfer problem was solved using an unstructured Control Volume based Finite Element Method (CVFEM). Peña et al. [12] introduced a method to reduce consumption of the steam used to ash cleaning of superheaters operating in coal-fired utility boilers. The methodology proposed in this paper was applied to the upper superheaters of a 350 MWe utility boiler. An experimental study of slagging and fouling mechanisms in a lignite-fired power plant was conducted by Panagiotidis et al. [13]. The results of the measurements demonstrated a general malfunction of the boiler due to massive slagging and fouling deposits. Studies showed that the experimental results are completely incompatible with the manufacturer's design operating data. Excessive slagging of water walls and superheaters was investigated by Bilirgen [14] for a pulverized coal-fired boiler when the off-design coal is burned. Boiler operating parameters and optimum soot blowing frequency were found to be very efficient in controlling furnace exit flue gas temperature.

Many theoretical and experimental studies concerning failures and estimation of residual life of superheater tubes have been published recently. Reduction of high-temperature corrosion on high-alloyed stainless steel superheaters by co-combustion of municipal sewage sludge in a fluidized bed boiler was analyzed by Karlsson et al. [15]. A new method for the residual life estimation of boiler tubes using steam-side oxide scale thickness is presented by Vikrant et al. [16]. The residual life of platen superheater tubes of T22 steel was predicted using oxide scale thickness, average metal temperature and creep master curve. Dynamic creep rupture of the secondary superheater tube in a coal-fired boiler by the decarburization and multilayer oxide scale buildup on both tube sides was investigated by Liu [17]. He found that the tube overheating temperature reached 900 °C and complete decarburization occurred throughout the tube. Shokouhmand et al. [18] carried out failure analysis of superheater tubes in utility boiler and showed that the cause of premature failure of tubes was long term overheating. Authors found that the mass flow rate of water sprayed into the attemperator exceeded the design value when the boiler operated at low load. Movahedi-Rad et al. [19] searched the reasons for superheater tube ruptures that were in service for over 20 years. Due to the use of low-grade oil fuel, sodium, sulfur and vanadium elements were identified at the outer tube surfaces, which caused permanent scale formation and reduction of the tube wall thickness.

A lot of studies are devoted to design and performance calculations of superheaters involving the calculation of the heat exchange area. Behbahani-nia et al. [20] used the log-mean temperature difference (LMTD) method to calculate the surface area