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Simulation of fluid heating in combustion chamber waterwalls of boilers for supercritical steam parameters

Wiesław Zima*, Marzena Nowak-Ocłoń, Paweł Ocłoń

Cracow University of Technology, Institute of Thermal Power Engineering, Al. Jana Pawła II 37, 31-864 Kraków, Poland

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ABSTRACT

This paper proposes a mathematical model with distributed parameters that allows to simulate the heat transfer processes in combustion chamber waterwalls of supercritical steam boilers. The model comprises solving the one-dimensional mass, momentum and energy conservation equations. The Forward Time Backward Space scheme is applied to discretize the governing equations. Two types of computational verification are performed for the proposed model. At first the model is validated with the analytical solution. The computational accuracy of the proposed model was tested for different time steps and grid size. At second, the results produced by the model were compared with those obtained when the Crank-Nicolson scheme is used to discretize the energy equation. In this case of results comparison the fluid flow and heat transfer phenomena were modeled for spirally wounded waterwall tubes of the combustion chamber in a supercritical boiler. A good agreement was found between the results produced by the proposed model and those obtained by using the analytical and Crank-Nicolson approaches. Therefore, the proposed model can be regarded as a useful tool for the design and monitoring of this type of heated surfaces. Moreover, the model can be applied in power units simulators.

1. Introduction

Nowadays the supercritical power plants attract a broad scientific attention due to the reduced fuel costs, high-efficiency and low environmental pollution [1–3]. Issues related to the modeling of flow and heat transfer processes occurring in the supercritical power boilers heating surfaces show the vast complexity and the strong non-linearity [4–7]. The complexity of the analysis of these processes is due to, inter alia, the high values of pressure and temperature and the complex shape of large heat transfer surfaces. Moreover, the fouling of the heating surfaces (especially from the flue-gas side) occurs during the boiler operation and worsens the heat transfer conditions considerably. The non-linearity is in turn a result of the temperature and pressure-dependent thermal properties of the fluid flowing inside a waterwall tubes. Those properties exhibit significant changes especially in the region of a vapor-liquid critical point. A model of an evaporation system in a supercritical W-shaped once-through boiler was proposed by Shu et al. [8]. It is a model with distributed parameters. Shu et al. developed the model on the basis of the three-dimensional temperature distribution and evaluated the heat flux and the waterwall tube wall temperature considering the heat-flux non-uniformity and variable frictional pressure drop coefficient. Pan et al. [9] indicated that the modeling and analysis of the heat transfer and fluid flow processes are fundamental for designing and operation of the waterwalls of the power boilers combustion chambers. They presented a mathematical model of fluid and wall heating that allows to determine the mass flux and the temperature of working fluid and the temperature of the vertical tube wall. Pan et al. solved the simplified one-dimensional governing equations including the continuity, momentum and energy equations. The model was applied to simulate fluid heating in vertical rifled tubes. Research, modeling and analysis were also subjected to the flow instability in parallel channels with supercritical parameters. Such type of investigations was carried out by Xiong et al. [10]. There are numerous mathematical models of heat transfer and fluid flow processes occurring in the entire power plant operating at supercritical parameters, for example [11,12]. However, those models are significantly simplified compared to real operating conditions of supercritical power plants.

This paper proposes an efficient one-dimensional mathematical model of fluid heating in waterwalls tubes of supercritical boilers.

* Corresponding author. Tel.: +48 12 6283653.
E-mail address: zima@mech.pk.edu.pl (W. Zima).

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Nomenclature

A	cross section area, m^2
c	specific heat, J/(kgK)
d	diameter, m
f	friction factor
g	gravity acceleration, m/s^2
G	mass flux, $kg/(m^2s)$
h	heat transfer coefficient, $W/(m^2K)$
i	enthalpy, kJ/kg
k	thermal conductivity, W/(mK)
L	length of the waterwall tube, m
$\dot{m}$	mass flow, kg/s
M	number of cross-sections
n	number of waterwall tubes
p	pressure, bar, MPa
q	heat flux, W/m^2
r	radius, m
s	tube pitch, m
t	fluid temperature, °C
U	circumference, m
w	flow velocity, m/s
z	axial coordinate, m

Greek symbols

β	CFL number
δ	thickness, m
ε	iteration tolerance
η	dimensionless time
φ	inclination angle of waterwall pipes
θ	wall temperature, °C
ρ	density, kg/m^3
τ	time, s
ζ	dimensionless coordinate
$\Delta\tau$	time step, s
Δz	spatial size of control volume, m

Subscripts

equiv	equivalent
in	inner
j	subsequent control volume
m	middle
o	outer
t	total
w	wall

The model uses the approach of distributed parameters. The spatial and temporal distributions of mass flux, pressure, temperature and enthalpy are obtained by solving the system of one-dimensional governing equations (mass, momentum and energy conservation). The governing equations are discretized using the FTBS (Forward Time Backward Space) scheme. The knowledge of fluid temperature will allow further to estimate the tube wall temperature. The correct prediction of tube wall temperature is important to avoid a potential tube wall overheating which can be caused by an excessive tube wall temperature increase that may occur mainly in the upper parts of waterwalls. The proposed model allows to consider the temperature and pressure-dependent thermophysical properties of fluid. Moreover, the model incorporates the effect of variable thermal load (changing with a tube length) and variable waterwall tubes inclination angle. The results of the computations performed using the proposed mathematical model are verified computationally throughout the comparison with the results of the analytical solution and the Crank-Nicolson method [13].

In the proposed model some simplifications are necessary to increase the computational efficiency and allow the model application in the on-line mode on the real object. The use of 3-D wall heat conduction model would increase the computation time, therefore the simplified model of fluid heating is presented in this study.

2. Model development

To determine the temporal and spatial variations of fluid mass flow rate, pressure and enthalpy the following set of governing equation has to be solved:

- Mass conservation equation

$$\frac{\partial \rho}{\partial \tau} = -\frac{1}{A}\frac{\partial \dot{m}}{\partial z}, \tag{1}$$

- Momentum conservation equation

$$\frac{\partial \dot{m}}{\partial \tau} = -\frac{1}{A}\frac{\partial}{\partial z}\left(\frac{\dot{m}^2}{\rho}\right) - A\left(\frac{\partial p}{\partial z} + \frac{\partial p_f}{\partial z} + \rho g \sin\varphi\right), \tag{2}$$

- Energy conservation equation

$$\frac{\partial i}{\partial \tau} = \left(1 - \frac{1}{\rho}\frac{\partial p}{\partial i}\right)^{-1}\left[\frac{\dot{m}}{A\rho}\left(\frac{1}{\rho}\frac{\partial p}{\partial z} - \frac{\partial i}{\partial z} + \frac{1}{\rho}\frac{\partial p_f}{\partial z}\right) + q_{equiv}\frac{U}{A\rho} - \frac{1}{A\rho}\frac{\partial p}{\partial \rho}\frac{\partial \dot{m}}{\partial z}\right]. \tag{3}$$

The fluid domain consists of M nodes located along the waterwall tube length. The governing equations are discretized by using the FTBS (Forward Time Backward Space) finite-difference scheme. This scheme is characterized in that the equations are integrated over the control volume formed between the two consecutive nodes j, $j-1$ of the numerical grid.

The time derivatives are approximated using the forward differencing scheme:

$$\frac{\partial \rho}{\partial \tau} = \frac{\rho_j^{\tau+\Delta\tau} - \rho_j^{\tau}}{\Delta\tau}, \quad \frac{\partial \dot{m}}{\partial \tau} = \frac{\dot{m}_j^{\tau+\Delta\tau} - \dot{m}_j^{\tau}}{\Delta\tau}, \quad \frac{\partial i}{\partial \tau} = \frac{i_j^{\tau+\Delta\tau} - i_j^{\tau}}{\Delta\tau}. \tag{4}$$

Spatial derivatives are approximated using the backward differencing scheme:

$$\frac{\partial \dot{m}}{\partial z} = \frac{\dot{m}_j^{\tau+\Delta\tau} - \dot{m}_{j-1}^{\tau+\Delta\tau}}{\Delta z}, \quad \frac{\partial p}{\partial z} = \frac{p_j^{\tau} - p_{j-1}^{\tau}}{\Delta z}, \quad \frac{\partial i}{\partial z} = \frac{i_j^{\tau+\Delta\tau} - i_{j-1}^{\tau+\Delta\tau}}{\Delta z}. \tag{5}$$

The following formulae on the fluid mass flow rate, pressure and enthalpy are obtained by replacing the derivatives in equations (1)–(3) with the suitable finite-difference schemes (4–5):