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A new 1D/3D model of conjugate heat transfer in waterwall tubes of power boiler combustion chamber

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Abstract

The paper presents the mathematical model for simulating heat transfer processes in waterwalls of supercritical steam boilers combustion chambers. The model is based on the distributed parameters. The proposed model enabling on-line simulation of transient heat and flow phenomena. The one dimensional model (1D) is solved for the fluid domain. A three-dimensional (3D) model is proposed for waterwall tubes with fins. In each analyzed cross-section of a waterwall tube with fins, there were specified 20 control volumes for which the energy balance equations were formulated in a 3D space. To verify the results obtained there were carried out computations for waterwalls of the combustion chamber of supercritical boiler operating in one of the Polish power plants. The proposed 1D-3D model allows obtaining fully satisfying results and may be applied to working in the on-line mode.

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Nomenclature

| Symbol | Description          | Unit          |
|--------|----------------------|---------------|
| A      | cross section area   | m²            |
| c      | specific heat        | J/(kgK)       |
| d      | diameter             | m             |

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1. Introduction.

The application of steam with supercritical parameters significantly improves the efficiency of a power unit. Modelling the transient heat transfer processes that occur on the heating surfaces of waterwall tubes of combustion chamber constitutes a complex issue [1-6]. The main problem is the nonlinearity resulting from changeable thermophysical properties of the fluids, complex shape of large heat transfer surfaces and the fouling of the heating surfaces. An especially strong nonlinearity is caused by a change in the density of water in the critical point area. In [7], an analysis is conducted of the impact of changes in this density on the processes occurring in the waterwall tubes. The waterwall tubes of combustion chamber are the most exposed to the danger of overheating. In order to determine the fluid and wall temperature it is necessary to analyze correctly the heat flow processes taking place in supercritical boiler waterwall tubes. Such analyses for unsteady states are the subject of numerous scientific elaborations, e.g. works [8-14]. The models presented in the literature need some modifications, mainly due to the fact that the authors did not include the non-uniform of heat load on the waterwall tubes outer circumference. Additionally, in case of waterwall there is not taken into account the fin connecting the waterwall tubes.

The currently most often numerical tools used for analyses the problems discussed above are the commercial CFD simulations [15-17]. The CFD codes enable determination of fluid temperature and velocity distributions as well as tube wall temperature distribution. Moreover, they also take into account complex three-dimensional (3D) models. The three-dimensionality mentioned makes using commercial CFD codes for modelling of non-steady heat exchange in combustion chamber waterwalls of supercritical boilers require large computational capabilities, which makes it impossible to use it in on-line applications. In this paper a new model which enables efficient simulation of heat transfer processes in waterwalls of combustion chambers of supercritical steam boilers is proposed. This model takes into account the non-uniform heating on the circumference of waterwall tube and along the tube length.

The presented hybrid 1D/3D model can be used successfully for on-line control of histories and distributions of temperatures of the fluid and the tube wall, together with the fins. The model involves a one-dimensional (1D) flow of fluid along the waterwall tube and three-dimensional approach for waterwall tubes with fins. Models similar to those presented herein are also used to simulate two-phase flows [18-19].
2. Model development

This section puts forward a mathematical 1D/3D model of the conjugate heat transfer in the waterwall tubes of combustion chambers power boilers. For the working fluid, one-dimensional (1D) equations describing the conservation equations are formulated and solved. In the case of a finned waterwall tube, the numerical analysis concerns a three-dimensional (3D) temperature field. Assuming that the fluid flow through all waterwall tubes is uniform, 1D/3D balance equations are formulated for a single tube. All the thermophysical properties of the fluid and the wall material of a waterwall tube with fins are calculated in the on-line mode. The condition for application of the model is the knowledge of distribution of heat load along the height of the boiler combustion chamber. This distribution may result from heat calculations performed for the combustion chamber (e.g. by means of the CKTI (Central Boiler and Turbine Institute) method [20]) or can be determined by means of thermometric inserts [21].

2.1. Fluid domain

In order to determine the histories of mass flow, pressures and enthalpy of the fluid along the waterwall tube the following set of governing equation has to be solved:

- Mass conservation equation

\[
\frac{\partial \rho}{\partial \tau} = - \frac{1}{A} \frac{\partial \dot{m}}{\partial z}
\]  

(1)

- Momentum conservation equation

\[
\frac{\partial \dot{m}}{\partial \tau} = \frac{1}{A} \frac{\partial}{\partial z} \left( \frac{m^2}{\rho} \right) - \left( \frac{\partial p}{\partial z} + \rho g \sin \alpha \right)
\]  

(2)

- Energy conservation equation

\[
\frac{\partial i}{\partial \tau} = \left( 1 - \frac{1}{\rho} \frac{\partial p}{\partial i} \right) \left[ \frac{m}{A \rho} \left( \frac{1}{\rho} \frac{\partial p}{\partial z} + \frac{1}{\rho} \frac{\partial i}{\partial z} \right) + q - \frac{1}{A \rho} \frac{\partial p}{\partial z} \frac{\partial \dot{m}}{\partial z} \right]
\]  

(3)

The governing equations presented above were solved by using the Forward Time Backward Space finite-difference scheme. As a result, relations are obtained that make it possible to determine histories of the working fluid mass flow, pressure and enthalpy [22]. Histories of the fluid temperature are then found as the function of pressure and enthalpy.

2.2. Three-dimensional model of waterwall tube

The waterwall tube with fins was divided on each \( j \) cross-section analyzed into 20 control volumes presented at Fig. 1.
Below energy balance equations for selected control volumes are presented (1, 11, 12, 20):

\[
c_{i,j}\rho_{i,j} \frac{\Delta \phi_i}{2} (r_{i+1}^2 - r_i^2) \frac{\Delta \theta_i}{\Delta z} = k_{i,j} \frac{\Delta \phi_i}{\Delta \theta_i} \frac{\Delta \theta_i}{\Delta r} r_i \Delta z + k_{i,j} \frac{\Delta \phi_i}{\Delta \theta_i} \frac{\Delta \theta_i}{\Delta r} r_i \Delta z
\]

\[
+ k_{i,j} \frac{\Delta \phi_i}{2} (r_{i+1}^2 - r_i^2) \frac{\Delta \theta_i}{\Delta z} + k_{i,j} \frac{\Delta \phi_i}{2} (r_{i+1}^2 - r_i^2) \frac{\Delta \theta_i}{\Delta z} + q_{i,j} \Delta \phi_i r_i \Delta z
\]

\[
c_{11,j} \rho_{11,j} \frac{\Delta \phi_i}{2} (r_{o,1}^2 - r_{o,2}^2) \frac{\Delta \theta_{11,j}}{\Delta z} = k_{11,j} \frac{\Delta \phi_i}{\Delta \theta_i} \frac{\Delta \theta_{11,j}}{\Delta r} r_o \Delta z + k_{11,j} \frac{\Delta \phi_i}{\Delta \theta_i} \frac{\Delta \theta_{11,j}}{\Delta r} r_o \Delta z
\]

\[
+ k_{11,j} \frac{\Delta \phi_i}{2} (r_{o,1}^2 - r_{o,2}^2) \frac{\Delta \theta_{11,j}}{\Delta z} + k_{11,j} \frac{\Delta \phi_i}{2} (r_{o,1}^2 - r_{o,2}^2) \frac{\Delta \theta_{11,j}}{\Delta z} + q_{11,j} \Delta \phi_i r_o \Delta z
\]

\[
c_{12,j} \rho_{12,j} \frac{\Delta \phi_i}{2} (r_{m,1}^2 - r_{m,2}^2) \frac{\Delta \theta_{12,j}}{\Delta z} = k_{12,j} \frac{\Delta \phi_i}{\Delta \theta_i} \frac{\Delta \theta_{12,j}}{\Delta r} r_m \Delta z + k_{12,j} \frac{\Delta \phi_i}{\Delta \theta_i} \frac{\Delta \theta_{12,j}}{\Delta r} r_m \Delta z
\]

\[
+ k_{12,j} \frac{\Delta \phi_i}{2} (r_{m,1}^2 - r_{m,2}^2) \frac{\Delta \theta_{12,j}}{\Delta z} + k_{12,j} \frac{\Delta \phi_i}{2} (r_{m,1}^2 - r_{m,2}^2) \frac{\Delta \theta_{12,j}}{\Delta z} + q_{12,j} \Delta \phi_i r_m \Delta z
\]

\[
c_{20,j} \rho_{20,j} \frac{\Delta \phi_i}{2} (r_{m,1}^2 - r_{m,2}^2) \frac{\Delta \theta_{20,j}}{\Delta z} = k_{20,j} \frac{\Delta \phi_i}{\Delta \theta_i} \frac{\Delta \theta_{20,j}}{\Delta r} r_m \Delta z + k_{20,j} \frac{\Delta \phi_i}{\Delta \theta_i} \frac{\Delta \theta_{20,j}}{\Delta r} r_m \Delta z
\]

\[
+ k_{20,j} \frac{\Delta \phi_i}{2} (r_{m,1}^2 - r_{m,2}^2) \frac{\Delta \theta_{20,j}}{\Delta z} + k_{20,j} \frac{\Delta \phi_i}{2} (r_{m,1}^2 - r_{m,2}^2) \frac{\Delta \theta_{20,j}}{\Delta z} + q_{20,j} \Delta \phi_i r_m \Delta z
\]

In the above dependencies:

\[
\Delta \phi_i = \frac{\pi \phi_i}{180}
\]

Equations (4)-(7) are solved using an explicit differential scheme. After transformations the following relations are obtained that make it possible to calculate temperature histories:

\[
\theta_{i+1,j}^{+\Delta t} = \theta_{i,j}^{+\Delta t} + \frac{\Delta \theta_{i,j}^{+\Delta t}}{\Delta z} \left[ k_{i,j} \frac{\theta_{i,j}^{+\Delta t} - \theta_{i-1,j}^{+\Delta t}}{\Delta \phi_i r_i \Delta z} r_i \Delta z + k_{i,j} \frac{\theta_{i,j}^{+\Delta t} - \theta_{i-1,j}^{+\Delta t}}{\Delta \phi_i r_i \Delta z} r_i \Delta z + q_{i,j} \Delta \phi_i r_i \Delta z \right]
\]

\[
+ \frac{k_{i,j}}{2} \left( r_{i+1}^2 - r_i^2 \right) \frac{\Delta \theta_{i,j}^{+\Delta t}}{\Delta z} + \frac{k_{i,j}}{2} \left( r_{i+1}^2 - r_i^2 \right) \frac{\Delta \theta_{i,j}^{+\Delta t}}{\Delta z} + q_{i,j} \Delta \phi_i r_i \Delta z
\]

\[
\theta_{11,j}^{+\Delta t} = \theta_{11,j}^{+\Delta t} + \frac{\Delta \theta_{11,j}^{+\Delta t}}{\Delta z} \left[ k_{11,j} \frac{\theta_{11,j}^{+\Delta t} - \theta_{10,j}^{+\Delta t}}{\Delta \phi_i r_o \Delta z} r_o \Delta z + k_{11,j} \frac{\theta_{11,j}^{+\Delta t} - \theta_{10,j}^{+\Delta t}}{\Delta \phi_i r_o \Delta z} r_o \Delta z \right]
\]

\[
+ \frac{k_{11,j}}{2} \left( r_{o,1}^2 - r_{o,2}^2 \right) \frac{\Delta \theta_{11,j}^{+\Delta t}}{\Delta z} + \frac{k_{11,j}}{2} \left( r_{o,1}^2 - r_{o,2}^2 \right) \frac{\Delta \theta_{11,j}^{+\Delta t}}{\Delta z} + q_{11,j} \Delta \phi_i r_o \Delta z
\]

\[
+ \frac{k_{11,j}}{2} \left( r_{o,1}^2 - r_{o,2}^2 \right) \frac{\Delta \theta_{11,j}^{+\Delta t}}{\Delta z} + \frac{k_{11,j}}{2} \left( r_{o,1}^2 - r_{o,2}^2 \right) \frac{\Delta \theta_{11,j}^{+\Delta t}}{\Delta z} + q_{11,j} \Delta \phi_i r_o \Delta z
\]
\[
\theta_{12,j}^{r+\Delta r} = \theta_{12,j}^{r} + \frac{\Delta r}{C_{12,j}^{r}} \left[ \frac{k_{12,j}^{r}}{r_{m}^{2}} \frac{\left( \theta_{13,j}^{r} - \theta_{12,j}^{r} \right)}{\Delta \phi_{j}^{r} r_{m}^{2}} \Delta r \Delta z + k_{12,j}^{r} \frac{\left( \theta_{1,j}^{r} - \theta_{12,j}^{r} \right)}{r_{m}^{2}} \Delta \phi_{j}^{r} r_{m}^{2} \Delta z \right]
\]

\[
+ k_{12,j}^{r} \frac{\Delta \phi_{j}^{r}}{2} \left( r_{o}^{2} - r_{m}^{2} \right) \frac{\left( \theta_{12,j+1}^{r} - \theta_{12,j}^{r} \right)}{\Delta z} + k_{12,j}^{r} \frac{\Delta \phi_{j}^{r}}{2} \left( r_{o}^{2} - r_{m}^{2} \right) \frac{\left( \theta_{1,j+1}^{r} - \theta_{12,j}^{r} \right)}{\Delta z} + h'_{j} \left( t_{j}^{r} - \theta_{12,j}^{r} \right) \Delta \phi_{j}^{r} r_{m}^{2} \Delta z
\]

\[
\theta_{20,j}^{r+\Delta r} = \theta_{20,j}^{r} + \frac{\Delta r}{C_{20,j}^{r}} \left[ \frac{k_{20,j}^{r}}{r_{m}^{2}} \frac{\left( \theta_{20,j}^{r} - \theta_{20,j}^{r} \right)}{\Delta \phi_{j}^{r} r_{m}^{2}} \Delta r \Delta z + k_{20,j}^{r} \frac{\left( \theta_{1,j}^{r} - \theta_{20,j}^{r} \right)}{r_{m}^{2}} \Delta \phi_{j}^{r} r_{m}^{2} \Delta z \right]
\]

\[
+ k_{20,j}^{r} \frac{\Delta \phi_{j}^{r}}{2} \left( r_{o}^{2} - r_{m}^{2} \right) \frac{\left( \theta_{20,j+1}^{r} - \theta_{20,j}^{r} \right)}{\Delta z} + k_{20,j}^{r} \frac{\Delta \phi_{j}^{r}}{2} \left( r_{o}^{2} - r_{m}^{2} \right) \frac{\left( \theta_{20,j+1}^{r} - \theta_{20,j}^{r} \right)}{\Delta z} + h'_{j} \left( t_{j}^{r} - \theta_{20,j}^{r} \right) \Delta \phi_{j}^{r} r_{m}^{2} \Delta z
\]

In the above equations the expressions \( C_{i,j}^{r} \) mean the products of amounts present on the left side of equations except for derivatives, e.g. for node no 1:

\[
C_{i,j}^{r} = c_{i,j}^{r} \rho_{i,j}^{r} \frac{\Delta \phi_{j}^{r}}{2} \left( r_{o}^{2} - r_{m}^{2} \right)
\]

### 3. Computational verification

The results obtained using the 1D/3D model presented in the previous section were verified by means of calculations performed for the combustion chamber waterwall tubes installed in a supercritical boiler currently operating in one of the Polish power plants. The parameters of this chamber were presented in the work [22]. Figure 2 presents the scheme of the analyzed combustion chamber and arrangement of one of the waterwall tubes is shown. It is installed at an angle, which changes at the chamber height of 49.4 m.

![Fig. 2. The scheme of the combustion chamber](image)

Fluid temperature distribution along the waterwall tube length for steady conditions is presented at Fig. 3. This distribution was determined as a function of pressure and enthalpy. The fluid temperature obtained at the outlet of combustion chamber waterwall amounts to 427°C.
Using derived 20 equations, similar to equations (9)-(12), the histories of the finned waterwall tube temperature are determined for 20 control volumes. Figs. 4-7 present histories obtained for selected cross sections and selected control volumes. The histories are presented for cross sections located 40, 80 and 120 m from the waterwall tube inlet and for the outlet cross section (165 m).

4. Summary
In the paper the mathematical model with distributed parameters presenting the hybrid model (1D-3D) heat transfer in waterwall tubes of combustion chambers of supercritical boilers is proposed. The knowledge of the wall temperature is very important and allows to control this temperature. This control is recommended especially in
upper sections of tubes where the danger of overheating is the highest. The presented model can be successfully applied in simulators of the supercritical power boiler operation.

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