Thermal flow analysis of vertical combustion chamber waterwall tubes operation

Marek Majdak[1,*], *Sławomir* Grądziel[1]
[1] Institute of Thermal Power Engineering, Cracow University of Technology, al. Jana Pawła II 37, 31-864 Kraków, Poland

Abstract. In this paper will be presented an algorithm that allows to determine the temperature distribution in a vertical pipe through which is flowing the medium with high temperature and pressure. The method of pipe division into control volumes presented in paper allows to determine the temperature distribution on the pipe cross-section and to determine changes in its value at the pipe height. The issue will be solved by taking into account the variability of the parameters of the material from which the pipe is made and the parameters of the fluid, depending on the temperature. The applied algorithm allows to determine the change in the value of individual parameters in time, due to which it is a useful tool for analysis of the operation of the system in the initial stage of its work, as well as with variable parameters of flow.

Nomenclature

A – cross-sectional area, m^2
c – specific heat, J/kgK
d – diameter, m
g - standard gravity, m/s^2
h – enthalpy, kJ/kg
k – thermal conductivity, W/mK
m – mass flow of the medium, kg/s
p – pressure, Pa
r– radius, m
t – temperature of the medium, °C
υ – velocity of the medium, m/s
z – height, m

Greek letters

α – heat transfer coefficient, W/m^2K
β – the angle of inclination of the waterwall tube, °
$\Delta\varphi$– characteristic angle for the finite volume under consideration, rad
Δz – height of finite volume, m
θ – wall temperature, °C
ρ – density, kg/m^3
τ – time, s

Subscripts

in – inner
m – medium
o – outer

Introduction

One of the most important operational problems occurring in high-power boilers is damage to the heat exchange surface in the combustion chamber, which in the case of boilers fired with solid fuels result in a higher frequency of maintenance shutdowns and the need to perform costly and difficult to correct repairs.

During boiler operation, waterwall pipes are exposed to large and uneven stresses, which in the boiler start-up phase result from the variability of boiler operation parameters over time. In the later period of boiler operation, stresses affecting waterwall pipes result from uneven thermal load of the surface through which heat exchange is implemented, as well as from variable flow conditions inside the pipes - depending on the type of power boiler, the pressure, mass flow and state of aggregation of the heat receiving medium - dependences allowing to determine the distribution of these parameters are presented in [1]. In many studies, it has been emphasized that the heat load changes at the width of the furnace chamber, so changing the pitch of the vertical waterwall pipes may allow to reduce the thermal stresses occurring in them. Another solution aimed at reducing thermal stresses is the use of internally rifled tubes instead of smooth tubes - a comparison of the heat exchange process for both types of tubes is presented in [2-4]. Detailed analysis of the operating parameters of individual boiler waterwall fragments may allow to reduce the frequency of damage occurring in them resulting from thermal stresses exceeding the permitted values.

Problem analysis

The problem of optimizing the arrangement of vertical waterwall tubes in the boiler furnace chamber will be analyzed (Fig. 1). The analysis will examine the thermal stresses occurring in the walls of the furnace chamber of the boiler, made in the form of vertical waterwall tubes

* Corresponding author: marek.majdak@mech.pk.edu.pl

connected with fins. The proposed mathematical model will take into account the variability of the thermophysical parameters of the medium and the metal from which the waterwall tubes are made, depending on the temperature. To determine the parameters of the factor circulating inside the waterwall pipes IAPWS IF97 water and steam tables have been implemented to the created mathematical model. Dependencies of thermophysical properties of steel, from which screen tubes were made, have been approximated based on available parameter tables determined by material manufacturers. For the analysis, it will be assumed that the boiler operates on supercritical parameters, and the heat load changes on the width of the furnace chamber, according to the results of tests carried out for fluidized bed boilers operating on supercritical parameters. The simplified distribution of the heat flux density in the cross-section of the furnace chamber is shown below (Fig. 2).

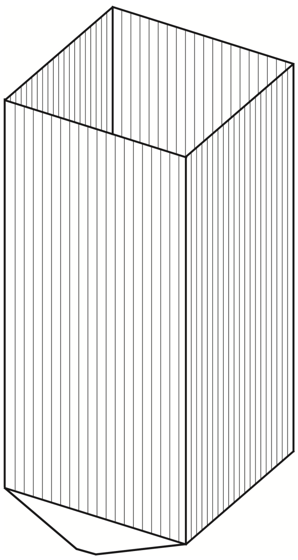

Fig. 1 The contour of the combustion chamber with vertical waterwall tubes

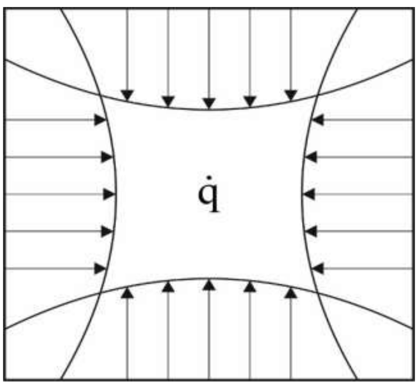

Fig. 2 The heat flux density distribution in the cross section of the combustion chamber

Optimization of the screen pipe arrangement is aimed at reducing the thermal stresses occurring in the furnace chamber walls, associated with significant temperature differences of the medium flowing through waterwall tubes occurring in boilers operating on supercritical parameters - in boilers with natural water circulation this phenomenon does not occur, because the temperature distribution of the medium in the width of the chamber is practically uniform.

The basic principles on which the calculation algorithm is based on the assumptions presented in [5] and [6-7]. The division of the analyzed waterwall tubes into control volumes by the method proposed in [6-7] has been presented in (Fig. 3). By using this, it is possible to determine the temperature distribution over the cross section of the pipe and the analysis of changes its value on the height of the tube. On the basis of the determined temperature distribution, an analysis of thermal stresses occurring in the waterwall tube will be carried out.

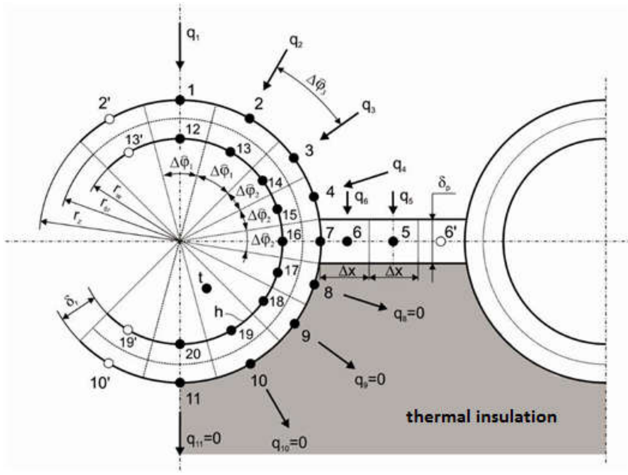

Fig. 3 The division of the cross-section of the analyzed waterwall tubes into control volumes

Equations of the energy balance for selected control volumes, allowing the creation of a matrix system describing the temperature distribution in a single screen tube are presented below:

$$c_{1,j}\rho_{1,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_o^{\,2}-r_m^{\,2}\right)\Delta z\frac{d\theta_{1,j}}{d\tau}=k_{1,j}\frac{\theta_{2,j}-\theta_{1,j}}{\Delta\widehat{\varphi}_1 r_o}\Delta r\Delta z+ k_{1,j}\frac{\theta_{12,j}-\theta_{1,j}}{\Delta r}\Delta\widehat{\varphi}_1 r_m\Delta z+k_{1,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_o^{\,2}-r_m^{\,2}\right)\frac{\theta_{1,j-1}-\theta_{1,j}}{\Delta z}+ k_{1,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_o^{\,2}-r_m^{\,2}\right)\frac{\theta_{1,j+1}-\theta_{1,j}}{\Delta z}+q_{1,j}\Delta\widehat{\varphi}_1 r_o\Delta z \quad (1)$$

$$c_{11,j}\rho_{11,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_o^{\,2}-r_m^{\,2}\right)\Delta z\frac{d\theta_{11,j}}{d\tau}=k_{11,j}\frac{\theta_{10,j}-\theta_{11,j}}{\Delta\widehat{\varphi}_1 r_o}\Delta r\Delta z+ k_{11,j}\frac{\theta_{20,j}-\theta_{11,j}}{\Delta r}\Delta\widehat{\varphi}_1 r_m\Delta z+k_{11,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_o^{\,2}-r_m^{\,2}\right)\frac{\theta_{11,j-1}-\theta_{11,j}}{\Delta z}+ k_{11,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_o^{\,2}-r_m^{\,2}\right)\frac{\theta_{11,j+1}-\theta_{11,j}}{\Delta z} \quad (2)$$

$$c_{12,j}\rho_{12,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_m^{\,2}-r_{in}^{\,2}\right)\Delta z\frac{d\theta_{12,j}}{d\tau}=k_{12,j}\frac{\theta_{13,j}-\theta_{12,j}}{\Delta\widehat{\varphi}_1 r_{in}}\Delta r\Delta z+ k_{12,j}\frac{\theta_{1,j}-\theta_{12,j}}{\Delta r}\Delta\widehat{\varphi}_1 r_m\Delta z+k_{12,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_o^{\,2}-r_m^{\,2}\right)\frac{\theta_{12,j-1}-\theta_{12,j}}{\Delta z}+ k_{12,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_o^{\,2}-r_m^{\,2}\right)\frac{\theta_{12,j+1}-\theta_{12,j}}{\Delta z}+\alpha_j\left(t_j-\theta_{12,j}\right)\Delta\widehat{\varphi}_1 r_{in}\Delta z \quad (3)$$

$$c_{20,j}\rho_{20,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_m^{\,2}-r_{in}^{\,2}\right)\Delta z\frac{d\theta_{20,j}}{d\tau}=k_{20,j}\frac{\theta_{19,j}-\theta_{20,j}}{\Delta\widehat{\varphi}_1 r_{in}}\Delta r\Delta z+$$
$$k_{20,j}\frac{\theta_{11,j}-\theta_{20,j}}{\Delta r}\Delta\widehat{\varphi}_1 r_m\Delta z+k_{20,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_o^{\,2}-r_m^{\,2}\right)\frac{\theta_{20,j-1}-\theta_{20,j}}{\Delta z}+ \quad (4)$$
$$k_{20,j}\frac{\Delta\widehat{\varphi}_1}{2}\left(r_o^{\,2}-r_m^{\,2}\right)\frac{\theta_{20,j+1}-\theta_{20,j}}{\Delta z}+\alpha_j\left(t_j-\theta_{20,j}\right)\Delta\widehat{\varphi}_1 r_{in}\Delta z$$

The next step in creating an algorithm allowing to determine the temperature distribution and distribution of stresses occurring on the furnace chamber wall was the implication of the equations describing the change of parameters flowing in the waterwall tubes given in [5] and their integration with the adopted division of analyzed elements into the control volumes described above. The applied equations of mass conservation, momentum balance, and energy balance for the factor flowing inside the analyzed waterwall tubes, presented in [5] in the form of differential equations with separated variables, are presented below:

$$\frac{\partial\dot{m}}{\partial z}=-A\frac{\partial\rho}{\partial\tau} \quad (5)$$

$$\frac{\partial}{\partial z}\left(\frac{\dot{m}^2}{A^2\rho}+p\right)=-\frac{1}{A}\frac{\partial\dot{m}}{\partial\tau}-\frac{\partial p_t}{\partial z}-\rho g sin\beta \quad (6)$$

$$\frac{\partial h}{\partial z}=\frac{\rho A}{\dot{m}}\left(-\frac{\partial h}{\partial\tau}+\frac{4\alpha\left(\theta-t\right)}{d_{in}\rho}\right) \quad (7)$$

$$\frac{dh_j^{\tau}}{dz}=\frac{\rho_j^{\tau-\Delta\tau}A}{\dot{m}_j^{\tau-\Delta\tau}}\left(-\frac{\partial h_j^{\tau}-\partial h_j^{\tau-\Delta\tau}}{\Delta\tau}+\frac{4\alpha_j^{\tau-\Delta\tau}\left(\theta_j^{\tau-\Delta\tau}-t_j^{\tau-\Delta\tau}\right)}{d_{in}\rho_j^{\tau-\Delta\tau}}\right) \quad (8)$$

$$\rho_j^{\,\tau}=f\left(h_j^{\,\tau},p_j^{\,\tau-\Delta\tau}\right) \quad (9)$$

$$\frac{d\dot{m}_j^{\,\tau}}{dz}=-A\frac{\rho_j^{\,\tau}-\rho_j^{\,\tau-\Delta\tau}}{\Delta\tau} \quad (10)$$

$$\frac{d}{dz}\left(\frac{\left(\dot{m}^2\right)_j^{\tau}}{A^2\rho_j^{\,\tau}}+p_j^{\,\tau}\right)=-\frac{1}{A}\frac{\dot{m}_j^{\,\tau}-\dot{m}_j^{\,\tau-\Delta\tau}}{\Delta\tau})- \quad (11)$$
$$\frac{dp_t}{dz}-\rho_j^{\,\tau}g sin\varphi$$

$$t_j^{\,\tau}=f\left(h_j^{\,\tau},\,p_j^{\,\tau}\right) \quad (12)$$

The proposed calculation algorithm, based on the above-described dependences, allows to determine the temperature distribution of the waterwall tube and the factor flowing through it, taking into account all the thermophysical properties of the medium and the furnace chamber wall in individual finite volumes. Below, on (Fig. 4 - 7), the temperature distributions for selected cross-sectional points of the waterwall tube will be presented, determined at different heights above the inlet of the medium to the waterwall tube.

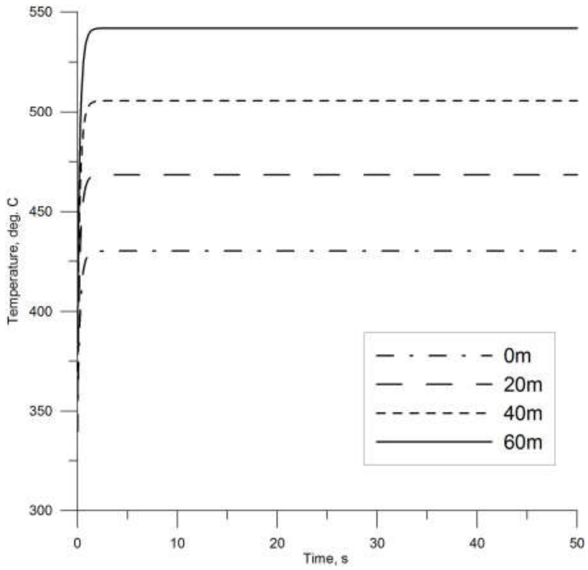

Fig. 4 Wall temperature distribution for point "1" depending on the height above the inlet of the tube

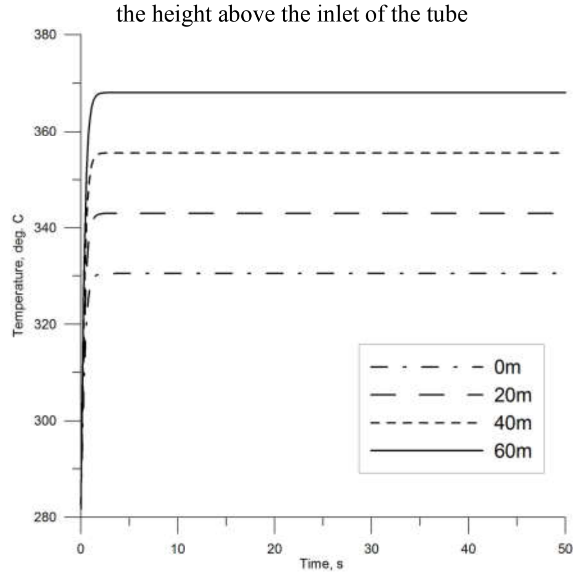

Fig. 5 Wall temperature distribution for point "11" depending on the height above the inlet of the tube

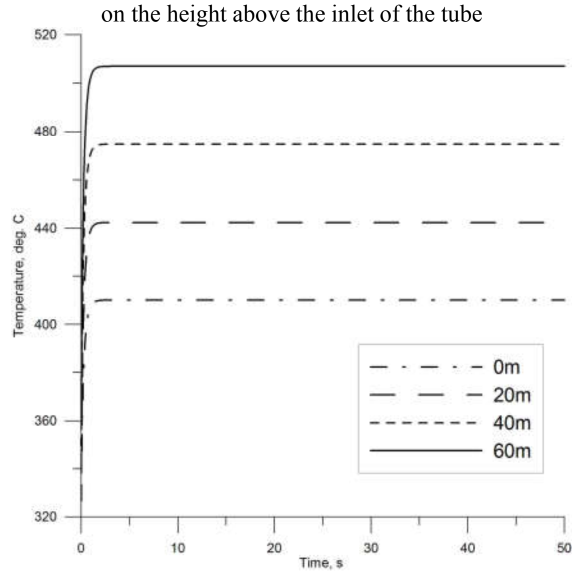

Fig. 6 Wall temperature distribution for point "12" depending on the height above the inlet of the tube

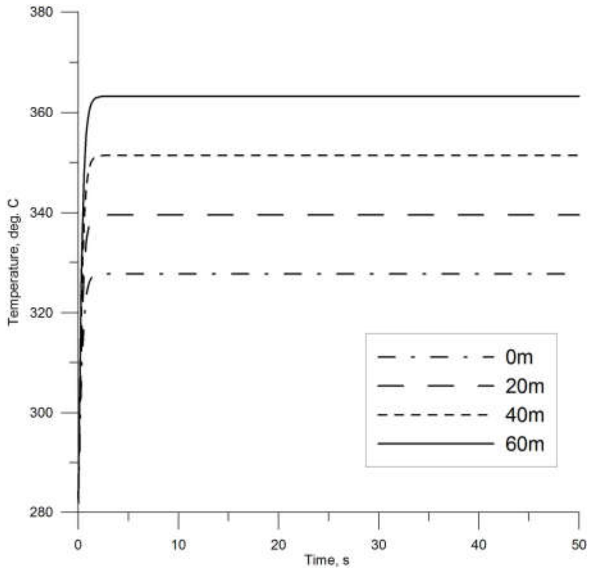

Fig. 7 Wall temperature distribution for point "20" depending on the height above the inlet of the tube

Summary

The paper presents the basic assumptions of the created algorithm allowing for the analysis of temperature distributions occurring in vertical waterwall tubes installed in the boiler's furnace chamber. Numerical calculations will have to take into account the variability of thermophysical parameters of waterwall tubes and the factor flowing in them, depending on the temperature in individual finite volumes. The numerical model will also take into account the difference in the mass flow of the medium flowing through the individual waterwall pipes and the change of the heat load value falling on individual waterwall tubes to accurately reflect the operating conditions of the boiler's evaporator. The results obtained using the numerical model will be the input data for the analysis of stresses occurring in vertical waterwall tubes.

References

1. S. Grądziel, K. Majewski, Chemical and Process Engineering **37**, 2, 199-213 (2016)
2. S. Grądziel, K. Majewski, Procedia Engineering **157**, 44-49 (2016)
3. K. Majewski, S. Grądziel, Chemical and Process Engineering **37**, 2, 251-260 (2016)
4. S. Grądziel, K. Majewski, Journal Heat Transfer Engineering **39**, 13-14, 1243-1250 (2018)
5. S. Grądziel, *Modeling of flow-thermal phenomena occurring in the boiler's evaporator with natural circulation* (in polish) (Wydawnictwo Politechniki Krakowskiej, Cracow, Poland, 2012)
6. W. Zima, M. Nowak-Ocłoń, P. Ocłoń*,* Energy **92**, 117–127 (2015)
7. W. Zima, M. Nowak-Ocłoń, P. Ocłoń, Energy **148**, 809-823 (2018)