Efficiency of heat transfer in the conditions of burning coal and water-coal fuel

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Abstract. The results of the numerical simulation of heat transfer from the combustion products of coal and coal-water fuels (CWF) to the internal environment. The mathematical simulation has been carried out on the sample of the pipe surfaces of the combustion chamber of the boiler unit. The change in the characteristics of heat transfer (change of thermochemical characteristics) in the conditions of formation of the ash deposits have been taken into account. According to the results of the numerical simulation, the comparative analysis of the efficiency of heat transfer has been carried out from the furnace environment to the inside pipe coolant (water, air, or water vapor) from the combustion of coal and coal-water fuels. It has been established that, in the initial period of the boiler unit operation during coal fuel combustion the efficiency of heat transfer from the combustion products of the internal environment is higher than when using CWF. The efficiency of heat transfer in CWF combustion conditions is more at large times ($\tau \geq 1.5$ hours) of the boiler unit. A significant decrease in heat flux from the combustion products to the inside pipe coolant in the case of coal combustion compared to CWF has been found. It has been proved that this is due primarily to the fact that massive and strong ash deposits are formed during coal combustion.

1. Introduction

Currently, most of the modern thermal power plants in Europe and North America use coal as the main fuel [1-3]. However, it is worth noting that the most significant problem of the modern boiler technology when burning coal is the formation of ash deposits [4, 5] on the heating surfaces, has not been solved yet. The deposition of slag is the main negative factor in the operation of the boiler unit [6]. High thermal resistance of ash leads to a significant decrease in the efficiency of heat transfer from the furnace environment to water or vapor. It is also worth noting that the sticking of ash, as a rule, occurs unevenly over the heat exchange surface. As a result, the pipe surface is heated unevenly, and a severe corrosion occurs [7].
Figure 1. Scheme of the problem solution area:

1 — a steel pipe wall; 2 — a layer of ash; 3 — a conventional symbol for the motion of the interface of the “ash layer — intrachamber sphere” system.

A number of works [8, 9] is devoted to modeling of the processes of slag deposition on the pipe heat exchange surfaces. In particular, in [9], the mechanisms of adhering ash on the heat transfer surfaces have been studied in some detail. However, it should be noted that in this case, a little attention has been paid to the problems of heat transfer in the conditions of contamination of the pipes of the boiler units with ash and slag. There are known works [10, 11] devoted to the problems of heat transfer as a result of ash deposits. But mainly they are devoted to the study of thermophysical properties (density (ρ), thermal conductivity (λ) and heat capacity (C)) of slag. Such studies are conducted at a constant thickness of the ash-slag layer. At the same time it is worth noting that in the process of depositing ash on the surface of heat exchange, the thickness of this layer as a rule is constantly changing. It is known [12] that the precipitation of slag proceeds under the conditions of crystallization of a liquid-slag melt. The latter is due to the presence of ash silicon oxide (SiO) and iron (FeO). The thermal effect of crystallization reaches 100 kJ/kg. Respectively, in the conditions of deposition of the ash the question arises about the appropriateness of including this heat in the simulation of heat transfer processes in the system “fluid — pipe wall and gas environment”.

One of the most promising methods of “low-ash” coal combustion is water-coal fuel technology (WCF). Due to the fact that WCF contains up to 50% water, the combustion temperature of such fuel is significantly lower (Tg ≤ 1100K) than the traditional pulverized-coal torch (Tg ≥ 1300K). In other words, the Tg burning of the water-coal fuel is lower than the slagging start temperature. However, to date, there has been no comparative analysis of the efficiency of heat transfer from the inside of the furnace to the heat carrier during the combustion of coal and water-coal fuel, under the conditions of ash precipitation and crystallization.

The purpose of the work is mathematical modeling of heat exchange processes in the “pipe surface — furnace environment” system in the conditions of formation of ash and slag deposits formed during the combustion of coal and water-coal fuel.

2. Formulation of the problem

The following problem is formulated based on the known [12] regularities of formation of ash deposits.

It is assumed that at the initial time (τ = 0 s) the heat exchange surface of the superheater is heated due to convection and emission of flue gases (Fig. 1). From the time τ = τsas the process of formation of ash and slag deposits begins. In this case, the ash crystallizes. To determine the efficiency of heat transfer in the system “inner pipe environment — a pipe wall — an ash layer — external environment”, the heat conduction problem has been solved.

The mathematical model corresponding to the above physical formulation of the problem includes the following system of differential equations of thermal conductivity in partial derivatives:

- a metal pipe

\[
\begin{align*}
C_1 \cdot \rho_1 \cdot \frac{\partial T}{\partial \tau} &= \frac{\lambda_1}{r} \cdot \frac{\partial}{\partial r} \left( r \cdot \frac{\partial T}{\partial r} \right) + \frac{\lambda_1}{r^2} \cdot \frac{\partial^2 T}{\partial \varphi^2} + \frac{\lambda_1}{\partial^2 T}{\partial z^2} \\
\text{for } r_{\text{dp}} < r < r_{\text{adp}}; \quad 0 < \varphi < 2 \cdot \pi; \quad 0 < z < L_z.
\end{align*}
\]
- a layer of ash deposits

\[
\frac{\partial T}{\partial \tau} = \frac{\lambda_2}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\lambda_2}{r^2} \frac{\partial^2 T}{\partial \varphi^2} + \lambda_2 \frac{\partial^2 T}{\partial z^2} \tag{2}
\]

\[r_{odp} < r < r_{oda}(\tau); \quad 0 < \varphi < 2 \cdot \pi; \quad 0 < z < L_z.\]

The change in the outer radius of the pipe (with taking into account the sediment layer) has been calculated using the expression:

\[r_{oda} = \int_0^\tau V_{rs} d\tau \tag{3}\]

Where \(V_{rs} = W_{rs}/\rho_s\) — a linear rate of depositions formation, \(W_{rs} = f(T)\) — a mass rate of ash formation kg/m²s ([13] for WCF, [12] when burning coal). The system (1) - (2) has been solved under the following boundary conditions.

Initial conditions:

\[\tau = 0; \quad r_{odp} < r < r_{odp}; \quad 0 < \varphi < 2 \cdot \pi; \quad 0 < z < L_z; \quad T(r, \varphi, z, 0) = T_0;\]

\[\tau = \tau_{ssa}; \quad r_{odp} < r < r_{oda}(\tau); \quad 0 < \varphi < 2 \cdot \pi; \quad 0 < z < L_z; \quad T(r, \varphi, z, 0) = T_a = T_s;\]

On the boundary of the system “pipe wall — ash layer” boundary the conditions of the fourth kind are fulfilled:

\[\lambda_d \frac{\partial T}{\partial r} \bigg|_{r=r_{ad}} = \lambda_d \frac{\partial T}{\partial r} \bigg|_{r=r_{ad}} \tag{4}\]

At the interface of the system “water vapor — a pipe wall”, convective heat exchange has been taken into account:

\[\lambda_4 \frac{\partial T}{\partial r} \bigg|_{r=r_{ad}} = \alpha \left[ T_a - T(r_{ad}, \varphi, z, \tau) \right] \tag{5}\]

At the interface of the system “pipe surface — furnace environment”, at \(\tau = 0\), the heat exchange law has been set:

\[\lambda_4 \frac{\partial T}{\partial r} \bigg|_{r=r_{ad}} = \alpha \left[ T_e - T(r_{ad}, \varphi, z, \tau) \right] + \varepsilon \cdot \sigma \left[ T_{es}^4 - T^4(r_{ad}, \varphi, z, \tau) \right] \tag{6}\]

Similar conditions have been formulated at the boundary of the system “ash deposits — the gaseous environment” at \(\tau > \tau_{ssa}\), taking into account the crystallization process of the slag melt:

\[\lambda_2 \frac{\partial T}{\partial r} \bigg|_{r=r_{ad}} = \alpha \left[ T_e - T(r_{ad}, \varphi, z, \tau) \right] + \varepsilon \cdot \sigma \left[ T_{es}^4 - T^4(r_{ad}, \varphi, z, \tau) \right] + Q_{cry} \cdot \rho_s \frac{dr}{dt} \tag{7}\]

\[\frac{\partial T}{\partial \varphi} \bigg|_{\varphi=0} = 0 \tag{8}\]

\[\frac{\partial T}{\partial \varphi} \bigg|_{\varphi=2\pi} = 0 \tag{9}\]

The problem has been solved in three stages. At the first, heat exchange has been calculated in the system “flue gases — a pipe surface — a heat carrier”. At the time \(\tau = \tau_{ssa}\), the calculation of the slag
deposition on the heating surface has begun. The formation of an ash layer with high thermal resistance has been taken into account. Later, heat transfer from the gaseous environment to the heat carrier inside the pipe has occurred through a layer of ash deposits. The thermal balance of the system “flue gases — a pipe surface — ash — a heat carrier” has been calculated according to the following scheme:

To analyze the efficiency of heat transfer through the ash sediments, heat has been calculated due to heat exchange from the internal surface of the pipe:

\[ Q_{kw} = \sum_{r=0}^{N_r} \sum_{\varphi=0}^{2\pi} \sum_{z=0}^{L_z} \left( \alpha_i \cdot \left[ T_i - T \left( r_{dip}, \varphi, z, t \right) \right] \right) \cdot r_{dip} \cdot h_f \cdot h_z \cdot \tau \]

The total amount of heat due to convection and radiation from the external environment to the pipe surface:

\[ Q_{k-rg} = \sum_{r=0}^{N_r} \sum_{\varphi=0}^{2\pi} \sum_{z=0}^{L_z} \left( \alpha_i \cdot \left[ T_i - T \left( r_{ods}, \varphi, z, t \right) \right] \right) + \varepsilon \cdot \sigma \cdot \left[ T_i - T \left( r_{ods}, \varphi, z, t \right) \right] \cdot r_{ods} \cdot h_f \cdot h_z \cdot \tau \]

After the beginning of the deposition of ash deposits, the total amount of heat supplied from the external gaseous environment:

\[ Q_{k-rs} = \sum_{r=0}^{N_r} \sum_{\varphi=0}^{2\pi} \sum_{z=0}^{L_z} \left( \alpha_i \cdot \left[ T_i - T \left( r_{ods}, \varphi, z, t \right) \right] \right) + \varepsilon \cdot \sigma \cdot \left[ T_i - T \left( r_{ods}, \varphi, z, t \right) \right] \cdot r_{ods} \cdot h_f \cdot h_z \cdot \tau \]

Heat of slag melt crystallization:

\[ Q_{cd} = \sum_{r=0}^{N_r} \sum_{\varphi=0}^{2\pi} \sum_{z=0}^{L_z} Q_{cry} \cdot \rho_d \cdot \frac{r_{ods}^{n+1} - r_{ods}^n}{r_{ods} \cdot h_f \cdot h_z \cdot \tau} \]

The heat accumulated in the material of the pipe walls due to the heat capacity:

\[ Q_{ahu} = \sum_{r=r_{dip}}^{r_{ods}} \sum_{\varphi=0}^{2\pi} \sum_{z=0}^{L_z} C_1 \cdot \rho_1 \cdot \left[ T_i \left( r, \varphi, z, t \right) - T_{0_1} \right] \cdot \left( r_{i}^2 - r_{i-1}^2 \right) \cdot h_z \cdot h_\varphi \]

Heat, accumulated in the slag layer due to the heat capacity:

\[ Q_{ahs} = \sum_{r=r_{ods}}^{r_{dip}} \sum_{\varphi=0}^{2\pi} \sum_{z=0}^{L_z} C_2 \cdot \rho_2 \cdot \left[ T \left( r, \varphi, z, t \right) - T_{0_2} \right] \cdot \left( r_{i}^2 - r_{i-1}^2 \right) \cdot h_z \cdot h_\varphi \]

The error in the heat balance of the pipe (without ash deposits) has been calculated from the following expression:

\[ E = \frac{Q_{kw} - Q_{k-rg} - Q_{ahu}}{Q_{kw}} \cdot 100\% \]

The thermal balance of the system “water vapor — a wall pipe — an ash layer — furnace environment” has been calculated from the expression:

\[ E = \frac{Q_{kw} - Q_{k-rs} - Q_{ahu} + Q_{ahs} + Q_{cd}}{Q_{kw} + Q_{ahs} + Q_{cd}} \cdot 100\% \]

3. Results and discussions

Figure 2 shows the dependences of the heat flux (q (t) W / (m²K)) from the inner wall of the pipe to the heat carrier (steam) under the conditions of formation of ash deposits on the heat exchange surfaces. The temperature of the combustion environment in the case of coal combustion has varied over a fairly wide range (from 800 to 1200 K with combustion of WCF, and from 1400 to 1700 K during the coal oxidation). It can be noted that in the time period up to \( \tau = 5 \cdot 10^3 \) s coal combustion is more effective than in the WCF. The latter is explained by the fact that the temperature of the coal torch is much higher than
that of the WCF. Accordingly, there are higher heat fluxes. However, the formation of ash deposits on the heating surfaces leads to a significant reduction in heat coming from the intra-furnace environment to the vapor. This is due to the high thermal resistance of the ash layer. As a result, after the expiration of a period of time $\tau \approx 5 \cdot 10^3 \, \text{s}$, the heat flux during the combustion of water-coal fuel begins to exceed the value $q(t)$ of the pulverized-coal furnace.

Figure 2 shows the results of a comparative analysis of the specific heat fluxes from the in-furnace gaseous environment to the in-pipe heat carrier with taking into account the ash crystallization. The analysis of the dependences shows that the thermal effect of crystallization has no effect practically on the heat transfer characteristics. This is due to the relatively small thermal effect of the phase transition ($\approx 100 \, \text{kJ} / \text{kg}$) [14].

4. Conclusion
According to the results of the mathematical modeling the dependences of heat fluxes in the external environment from time have been obtained by burning two types of fuel (pulverized coal and water-coal fuel). It has been established that in the initial period of time ($\tau = 100000 \, \text{s}$) operation of a steam boiler burning coal (pulverized) fuel is more efficiently than hydrocarbon. This is caused by the higher temperature of the combustion environment. However, during operation of the boiler a longer period of time, the coefficient of the heat combustion use at the water-coal boilers is higher than in the pulverized coal boilers. This is due to the fact that when burning coal fuel on the surface of the steam heater pipes, solid ash deposits are formed, which substantially worsen the heat transfer conditions. In the case of WCF combustion, such deposits are formed much less. In the case of WCF burning such deposits appear much less.

![Figure 2](image_url)

**Figure 2.** The dependence of the heat flux value from the inner wall of the pipe to the heat carrier on the operating time of the boiler unit, at ambient temperatures:

1, 2 - $T_e=1700 \, \text{K}$; 3 - $T_e=1200 \, \text{K}$; 4,5 - $T_e=1600 \, \text{K}$; 6 - $T_e=1100 \, \text{K}$; 7 - $T_e=1000 \, \text{K}$; 8, 9 - $T_e=1500 \, \text{K}$; 10 - $T_e=900 \, \text{K}$; 11 - $T_e=800 \, \text{K}$; 12,13 - $T_e=1400 \, \text{K}$;

(1, 2, 4, 5, 8, 9, 12, 13) – coal burning; (3, 6, 7, 10, 11) – WCF.
The analysis of the effect of the crystallization processes of the slag melt, when deposited on the heating surface, has showed that it can be ignored in calculating the heat transfer characteristics. This is explained by the small value of the thermal effect of the phase transition (≤100 kJ / kg).

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