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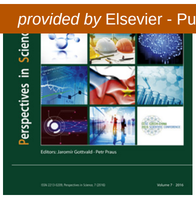

Study of thermal-flow processes in ash cooler cooperating with CFB boiler☆

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Summary The article presents an example of thermal-flow analysis of the bottom ash cooler cooperating with the circulating fluidized bed boiler. There is presented a mathematical model of series-parallel hydraulic system supplying the ash cooler in cooling water. The numerical calculations indicate an influence of changes of the pipeline geometrical parameters on the cooling water flow rate in the system. Paper discusses the methodology of the studies and presents examples of the results of thermal balance calculations based on the results of measurements. The numerical results of the thermal-flow analysis in comparison with the measurements on the object indicate that the presented approach could be used as a diagnostic tool investigating the technical state of the bottom ash cooler.

Introduction

>The basic element of a conventional power plant is a boiler where chemical energy of fossil fuels (hard coal, lignite) is converted into a heat. As a result of combustion processes occurring in the boiler, a slag is produced. Later on, it must be removed from the combustion chamber and pre-cooled before its final storage. The mass flow rate of the discharged slag can vary from a few to several kg/s depending on the type of boiler and its actual thermal output as well as the mass flow rate and technical analysis of the fuel. For technical reasons, the transported from the combustion chamber slag requires pre-cooling to a temperature of about 100—120 °C. It is done in an ash cooler. The construction, number and location of ash coolers is closely related to the type of combustion chamber and is an important element of the power boiler (Kruczek, 2001).

In order to remove the heat from slag, ash coolers are supplied with cooling water circulated usually in a

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serial-parallel hydraulic system. A volumetric flow rate of cooling water has a decisive influence on the final temperature of transported slag. In most solutions, water is circulating in a closed system cooperating with cooling towers and its temperature is determined by the atmospheric conditions and the actual operating parameters of cooling tower. Moreover, hydraulic systems of cooling water are designed according to the optimization criteria in order to achieve maximum efficiency for nominal thermal output of the boiler if it operates under standard thermodynamic parameters for design fuel composition. Often, however, this approach ignores the fact that during operation the installation is subject to the processes leading to the deterioration of its nominal working conditions. An example might be to change the water mass flow rate to ash coolers resulting from the reconstruction of the hydraulic system, deterioration of circulating pump characteristics or build up of mineral deposits in pipelines of installation. In addition, temporary deterioration of the quality of fuel could cause the increase of its mineral content. It may result an increase in the mass flow rate of slag discharged from the boiler, and thus increasing demand for cooling water flow rate. All these factors affect in a significant way to the deterioration of the operating parameters of ash coolers and final temperature of transported slag (Nowak, 2003).

The article presents an example of thermal-flow analysis of the bottom ash cooler cooperating with the circulating fluidized bed boiler. It discusses the methodology of the studies and presents examples of the results of thermal balance calculations based on the results of measurements (Andruszkiewicz et al., 2014a,b).

Construction of ash cooler

In the paper there is discussed an ash cooling system of a circulating fluidized bed (CFB) boiler which consist of two bottom ash coolers denoted by SAC-L and SAC-R (respectively left and right bottom ash cooler). Fig. 1 shows schematically the most important elements of the SAC-R ash cooler — two screw coolers (designated by the acronym SC-L and SC-R on the left diagram in Fig. 1). The right diagram of Fig. 1 shows a schematic side view of the bottom ash cooler with an indication of: feeding hot ash (1), and discharging the pre-cooled ash (6), inlet and outlet of cooling water supplying SC-L ((2) and (3) respectively), inlet and outlet of the cooling water flowing through the outer walls of the cooler. The ash is delivered directly from the combustion chamber (1) and split onto two screw coolers (SC-L and SC-R) and then transported to the point (6). During its motion along the screw, ash is gradually cooled in blades, shaft pipe and outer walls.

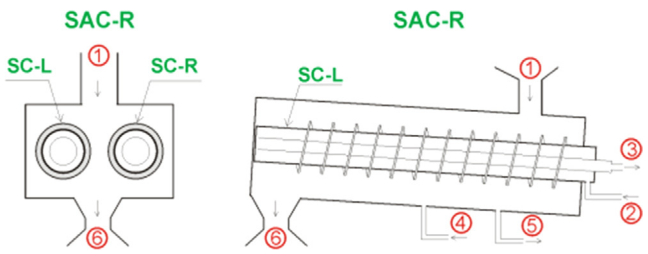

Figure 1 The main elements of the construction of the bottom ash cooler (SAC-R): two screw coolers (SC-L and SC-R), inlet and outlet of ash ((1) and (6) respectively), and inlet and outlet of cooling water cooling ((2, 4) and (3, 5) respectively).

Operational conditions of fluidized bed boiler are connected with the constant mass of the inert material circulating in the combustion chamber. This mass has a critical influence on pressure drop and temperature profile along the height of the boiler. Maintaining a proper weight of circulating bed leads to the state of fast fluidization, which guarantees the maintenance of a uniform temperature distribution along the height of combustion chamber.

Cooling water installation

An example of a series-parallel system of the cooling water propagation to two bottom ash coolers of a fluidized bed boiler is shown in Fig. 2.

Each of the bottom ash coolers (SAC-L and SAC-R) consists of two screw coolers (SC-L and SC-R) supplied by cooling water volumetric flow rates respectively: q_{v21}, q_{v22} and q_{v41}, q_{v42}. The flow rates which cool down the outer walls of coolers are denoted by q_{v23} and q_{v43} respectively. Cooling water is taken from the common collector and pumped into the system through a pump which gives at the inlet to the system static pressure p_1. The pump discharge is calculated based on the pressure difference $\Delta p_p = (p_1 - p_0)$. At the exit from the system static pressure is p_2. The pressure difference $\Delta p = (p_1 - p_2)$ forces to circulate the cooling water in various branches of the system. Cooling water is supplied to (and removed from) each branch by pipe having a diameter of $\phi 160$ (parts R_{01}, R_{03}, R_{09}, R_{10}), and next by pipe $\phi 120$ (parts R_{02}, R_{04}—R_{08}). The pipe which delivers cooling water directly to the ash coolers and its outer walls has a diameter of $\phi 60$ (parts R_{21}—R_{23} and R_{41}—R_{43}).

In order to formulate a mathematical model of series-parallel network the flow resistances R_i have to be assigned to each branches of the system. The resultant resistances on the following sections of the installation are the sum of local friction and minor losses at these sections. The coefficients

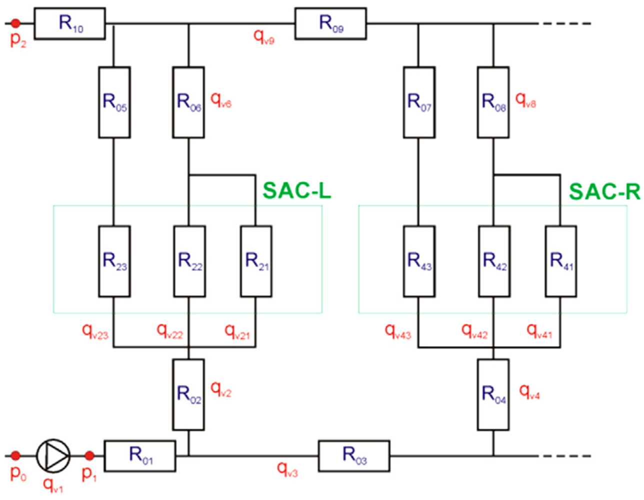

Figure 2 An example of a series-parallel system of the cooling water propagation to two bottom ash coolers of a CFB boiler.

of minor losses were selected on the basis of literature data and the coefficients of friction losses were calculated from Blasius formula in the range of turbulent flow (Jeżowiecka-Kabsch and Szewczyk, 2001). The mathematical model of network finally consists of eleven non-linear algebraic equations including:

- 5 balance equations describing water distribution in individual joints,
- 5 equations describing pressure losses in the hydraulic network meshes,
- One equation describing the pressure drop in the selected branch between the inlet and outlet point of the system (respectively p_1 and p_2 points).

The system of eleven non-linear algebraic equations was solved iteratively by Newton's method (Mathews and Fink, 1999). Newton's method allows to determine the flow rates q_v in the process of successive approximations with any predetermine precision ε. It should be noted that the flow resistances R_i depend on the friction losses coefficients λ_i, which are functions of the Reynolds number (and thus the flow rate). In the process of solving the abovementioned set of eleven nonlinear equations one must therefore update value of λ_i coefficients according to the actual values of flow rates q_v before the next iteration step.

The above described mathematical model of hydraulic network was used to determine the characteristics of the cooling water flow rates for both bottom ash coolers SAC-L and SAC-R (respectively q_{v2} and q_{v4}). Example of calculation results is shown in Figs. 3 and 4.

Blue line at Figs. 3 and 4 show the current characteristic for both ash coolers SAC-L and SAC-R. Introducing to the mathematical model geometrical modifications of the system like larger diameters of the pipelines: $\phi160 \rightarrow \phi250$ (parts R_{01}, R_{03}, R_{09}, R_{10}), $\phi120 \rightarrow \phi180$ (parts R_{02}, R_{04}-R_{08}) and $\phi60 \rightarrow \phi80$ (pipes which deliver cooling water directly to the ash coolers) red line is obtained.

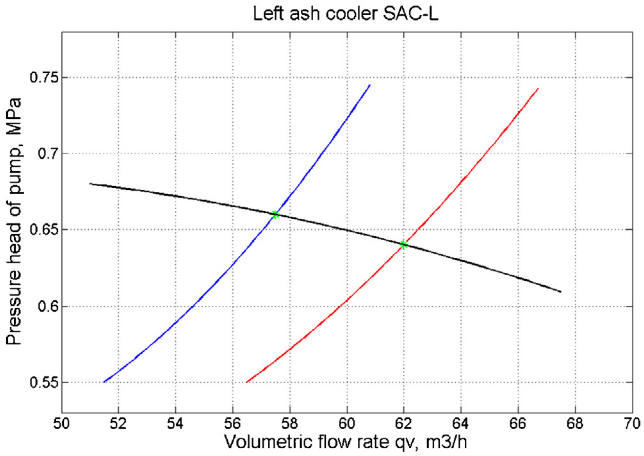

Figure 3 Characteristics for bottom ash cooler SAC-L as a function of cooling water flow rate received from the mathematical model (blue line — current state, red line — installation after modifications). Black line indicates cooling water pump characteristic.

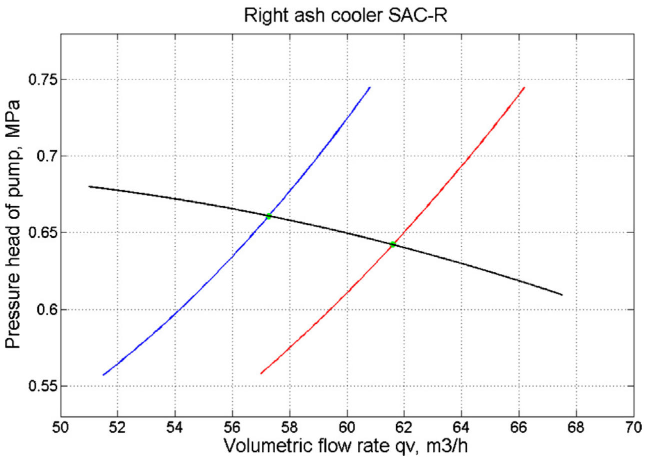

Figure 4 Characteristics for bottom ash cooler SAC-R as a function of cooling water flow rate received from the mathematical model (blue line — current state, red line — installation after modifications). Black line indicates cooling water pump characteristic.

Cross sections of blue and red line with cooling water pump characteristic (black line at Figs. 3 and 4) indicate the flow rates of cooling water in the installation at current state and after modifications. For current working parameters, the mathematical model gave $q_{v2} = 57.4\,\mathrm{m}^3/\mathrm{h}$ and $q_{v4} = 57.2\,\mathrm{m}^3/\mathrm{h}$ for SAC-L and SAC-R respectively.

In order to validate the results of a mathematical model and determine the thermal balance of the bottom ash cooler the real object has been studied. Fig. 5 shows a fragment of cooling water system (supplying SAC-R) with marking of individual pipelines.

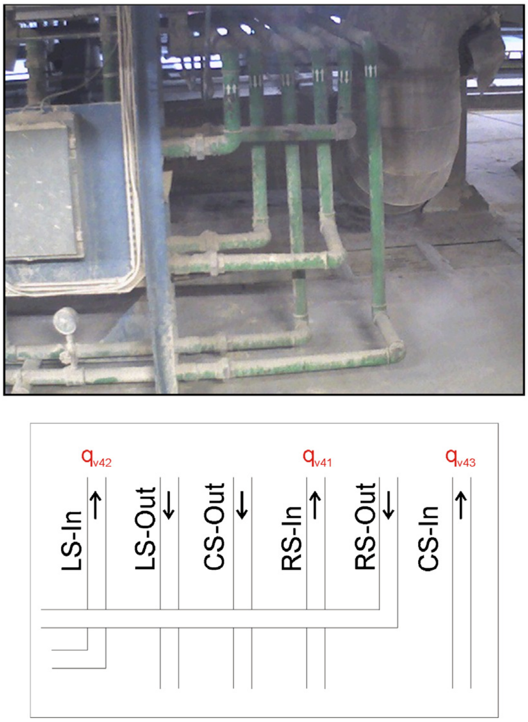

Figure 5 System of pipelines supplying of a SAC-R bottom ash cooler in cooling water together with applied notation.

Table 1 Examples of measurement results of temperatures and mass flow rates for bottom ash coolers SAC-L and SAC-R.

Quantity	SAC-L	SAC-R
t_1, SC-R, °C	23.6	23.3
t_2, SC-R, °C	39.8	38.5
t_1, SC-L, °C	23.8	23.6
t_2, SC-L, °C	40.1	41.0
t_1, BC, °C	22.8	21.2
t_2, BC, °C	32.6	39.1
q_{v1}, m^3/h	20.6	21.8
q_{v2}, m^3/h	21.3	22.1
q_{v3}, m^3/h	14.2	13.1

Examples of measurement results are shown in Table 1. The mass flow rates q_{v1}, q_{v2} and q_{v3} correspond to the values q_{v21}, q_{v22}, q_{v23} and q_{v41}, q_{v42}, q_{v43} respectively. BC designation refers to the outer walls of the ash cooler.

The heat flux received by individual bottom coolers can be calculated taking the specific heat of water $c_w = 4.19\,kJ/kg\,K$. Then, basing on Table 1, the heat flux received by the cooler SAC-R is 1.10 MW and by the SAC-L — 0.93 MW giving totally of 2.03 MW.

During the measurements, the mass flow of the coal was 35.2 kg/s and the mass flow rate of limestone 2.4 kg/s. Technical analysis showed that the lignite consists of: 41.4% of moisture, 13.8% of ash, 11.6% of volatiles and 33.2% of char. Assuming that the ash separated in a percentage on: fly ash — 48% and slag — 52% of its total weight, one can calculate the heat flux of the cooled slag in both coolers. Assuming the specific heat of the slag is 958 J/kgK, its temperature measured at the inlet of the ash cooler is 640.3 °C and outlet temperature is 75.5 °C there was calculated that the cooled ash release the heat flow equals to 2.04 MW.

Conclusion

The study presents an example of thermal-flow analysis of bottom ash coolers cooperating with CFB boiler. The results of a mathematical model of series-parallel hydraulic system showed good agreement of flow rates with the results of measurements on a real object. Thermal analysis showed that the total heat flux released at both bottom ash cooler is at the level of 2 MW. Presented model could be used as a diagnostic tool to investigate the technical state of ash coolers.

Conflict of interest

The authors declare that there is no conflict of interest.

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