ARCHIWUM ENERGETYKI tom XLII(2012), nr 2, 85–92

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Modelling of platen superheaters in a circulating fluidized bed boiler at different loads

A second stage steam superheater is a platen superheater made from so-called 'double omega' tubes. The superheater is a three-pass tube heat exchanger. Each pass is made from different low-alloy steel. In the paper, the temperature distributions of the steam and tube wall in the platen superheater were computed at different partial loads of a circulating fluidized bed (CFB) boiler.

1 Introduction

The article presents the steady-state analysis of a superheater's 'double omega' tubes which was carried out using STAR-CCM+ software [1]. The heat transfer in the platen superheaters of circulating fluidized bed (CFB) boilers is a complex problem [2,3]. There is no general calculation method which can be applied to the design and performance calculation. Larger units are built based on the experience gained earlier [4,5]. The heat transfer coefficient on the side of the fluidized bed can be calculated only very approximately. Based on the data for

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different loads, the heat transfer coefficient was determined as a function of the boiler load. The heat transfer coefficient was determined from the condition that the same increase in steam temperature in the superheater is obtained from measurements and from 3D computational fluid dynamics (CFD) simulations. Correlations were found for the flue gas side heat transfer coefficient as a function of boiler load, fluidized bed temperature, and fluidization velocity. The results presented in the paper can be used in the design and operation of CFB boilers.

2 CFD simulation of the three-pass superheater

Numerical simulation of the three-pass superheater was carried out in steady-state for different partial loads of the boiler. The superheater double omega is the second stage platen superheater in a CFB boiler and is located in the upper part of the combustion chamber. The steam in the platen flows in serial through three passes and each pass includes three parallel double omega tubes made from different low-alloy steels. The platen is formed of 27 coils, each of which consists of three tubes (passes). The overall number of serial tubes in one plate is equal to 81. Figure 1 presents one platen and the specified direction of the steam flow through the three serial tubes.

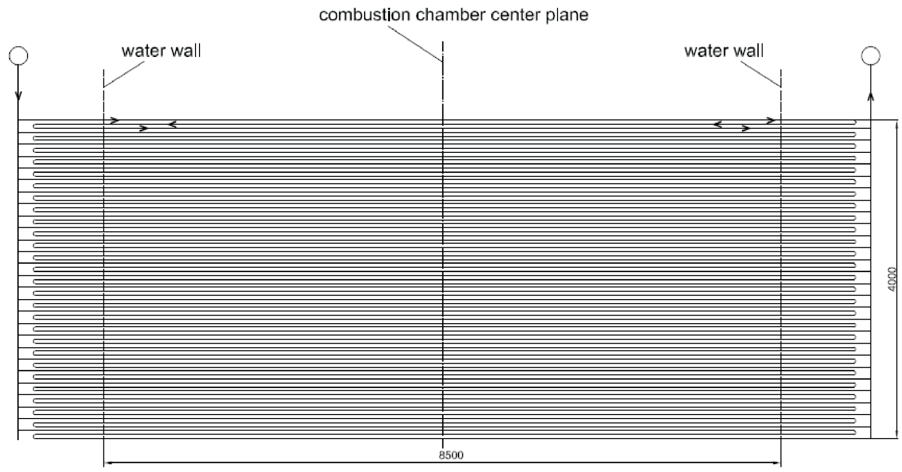

Figure 1. The platen which includes 81 serial tubes forms the 27 three-pass tube sets.

Each pass is made from different low alloy steel grades and has a different inner diameter. The first pass is made from 15Mo3 steel, the second from 13CrMo44 steel, and the third from 10CrMo910 steel (Fig. 2a). The inner diameter of the first pass is equal to 26.8 mm, that of the second, 25.4 mm, and that of the third, 23.8 mm. The steel properties were assumed to be temperature dependent. The thermal conductivity coefficient, k, of the 15Mo3, 13CrMo44, and 10CrMo910 steels is a function of temperature and is shown in Fig. 2b.

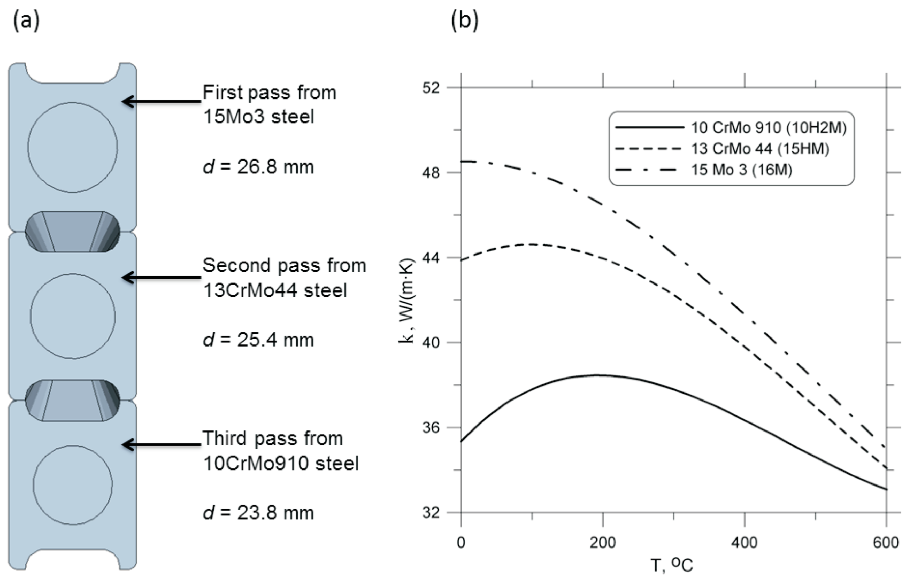

Figure 2. Three passes made from different steels and with different inner diameters (a) and thermal conductivity coefficients as a function of temperature (b).

CFD modelling of the three-pass superheater was conducted to determine the wall temperature as well as the velocity, pressure, and temperature of the steam flowing inside the superheater tubes. The fluidized bed was not modelled because the temperature of the circulating bed does not change over the combustion chamber height. The temperature of the steam at the inlet and outlet of the superheater, the steam pressure, and the mass flow rate are known from measurements. The heat transfer coefficient on the flue gas side has been chosen, so that the computed increase in the steam temperature was the same as the result of measurement from the experiment. The simulation input data for all analysed loads of the boiler are described in Tab. 1. The results of CFD simulation for 100% and 60% loads are depicted in Fig. 3.

Inspection of the results indicates that the highest temperatures occur at the corners of the omega tube. The increases in steam temperature in the first, second, and third passes for 100% load are 30.5, 37.0, and 40.0 K, respectively. For 60% load the steam temperature differences between the outlets and inlets of

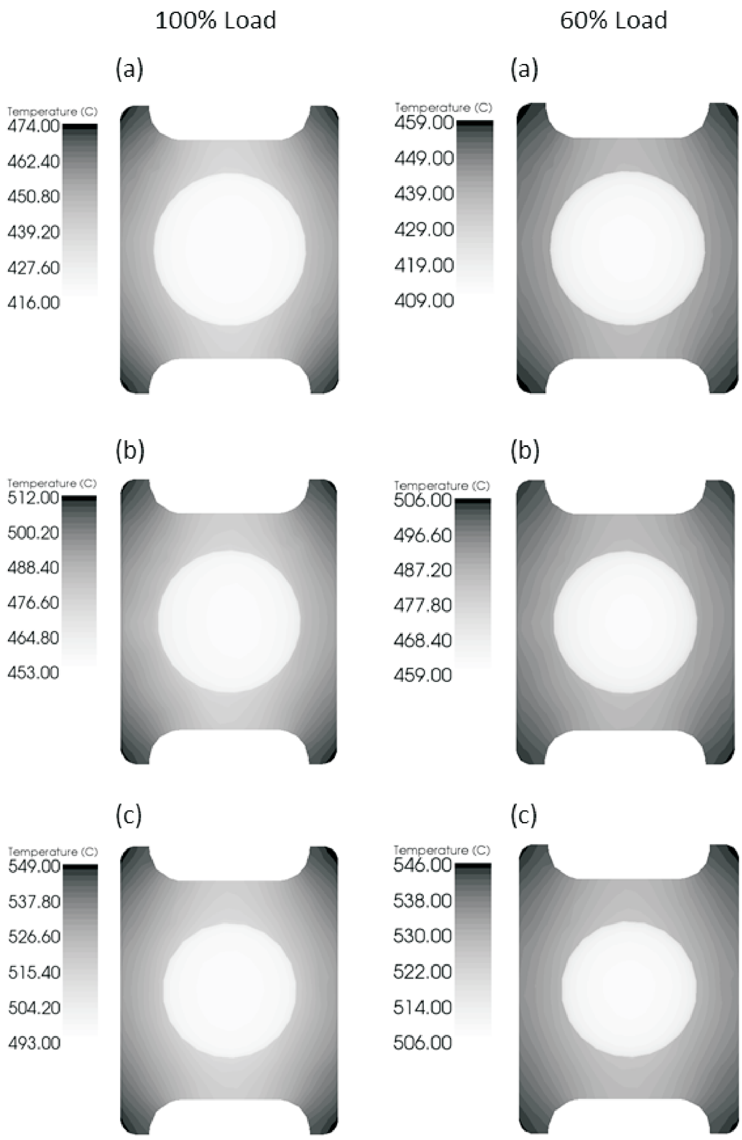

Figure 3. Temperature distribution at the outlet cross section of the first (a), second (b), and third (c) pass of a superheater for 100% and 60% loads.

Table 1. Input data for all partial loads.

Load, %	100	98.8	83.7	73.5	60	48.7	35
Mass flow rate per tube, kg/s	0.4302	0.4239	0.3474	0.3021	0.2448	0.1981	0.1486
Inlet steam pressure, MPa	16	16	13.5	11.9	9.8	7.9	7.5
Inlet steam temperature, °C	385.5	385.1	373.3	370	363.3	362.1	387.1
Flue gas temperature, °C	850	849	824	804	767	720	645

the passes are larger and amount to 45.7, 50.0, and 47.0 K, respectively. Changes in steam and tube wall temperatures along the steam flow path are shown in Fig. 4.

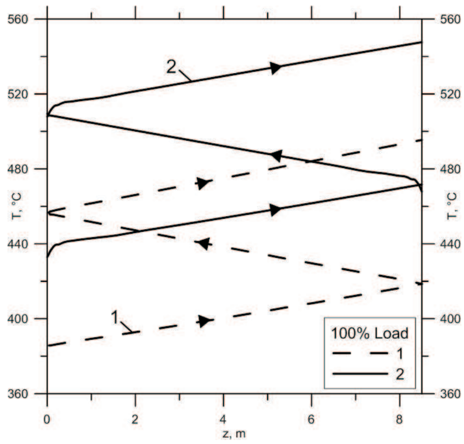

Figure 4. Changes in mass average steam temperature and tube wall temperature at the tube corner along the steam flow path: 1 – steam; 2 – tube wall temperature at the corner.

The maximum wall temperatures occur at the outlet of the third pass. These temperatures are lower than the allowable temperature limit for the 10CrMo910 steel. The tube temperatures at the inlets to the second and third passes are lower because of developing flow at the inlet region of the tube (Fig. 4). At the inlet region, the steam-side heat transfer coefficient is higher and as a consequence the tube wall temperature is lower.

3 Determination of the heat transfer coefficient

The efficiency of the boiler is expressed by the boiler load parameter, which represents the percentage of the maximum steam flow possible in the boiler. The change in the boiler load is connected with changing the heat flux absorbed by the superheaters. The heat flux is dependent on the temperature and velocity of the flue gas in combustion chamber. Table 2 presents the parameters of the fluidized bed at different partial loads of the boiler.

Table 2. The parameters of the fluidized bed at different partial loads of the boiler.

Load, %	100	98.8	83.7	73.5	60	48.7	35
Flue gas temperature, °C	850	849	824	804	767	720	645
Flue gas velocity, m/s	5.9	5.8	5.1	4.7	4.1	3.7	3.4
Flue gas-side heat transfer coefficient, W/(m^2·K)	174	172	156	144	130	115	104

During boiler operation the partial load changes over a wide range, from 35% to the maximum performance, (100%). In Figure 5, the change in the heat transfer coefficient h as a function of boiler load is presented graphically.

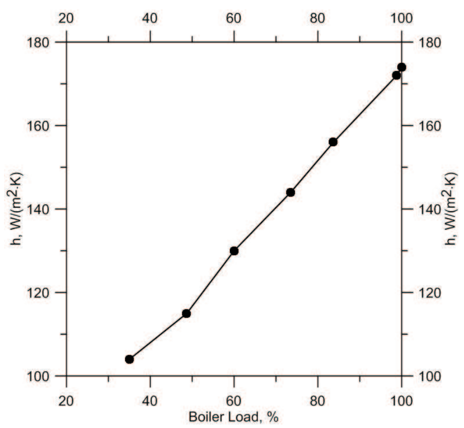

Figure 5. The heat transfer coefficient as a function of the boiler load.

The estimation of the heat transfer coefficient, h, on the side of fluidized bed is a complex problem. The value of the heat transfer coefficient, in the surfaces located in the upper part of the furnace of a CFB boiler, is dependent on the temperature in the combustion chamber and the velocity of the flue gas. The first part of the coefficient represents a radiative heat transfer between flue gas and superheaters and the second is responsible for a convective heat transfer and strongly depends on the flue gas velocity in the combustion chamber. The values of the heat transfer coefficient were determined from simulation in steady-state for different boiler loads and corresponding boundary conditions (Tab. 2). The fluidized bed was not modelled in the simulation because the temperature in the combustion chamber along the height of the platen superheater was constant. The flue gas side was modelled as a third kind of boundary condition and to define this condition at the boundary, the flue gas temperature and heat transfer coefficient were used. Figures 6 and 7 show the change in the heat transfer coefficient as a function of the flue gas temperature and velocity in the circulating fluidized bed.

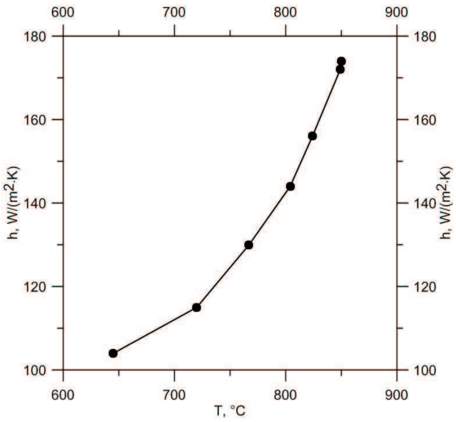

Figure 6. The heat transfer coefficient as a function of the flue gas temperature.

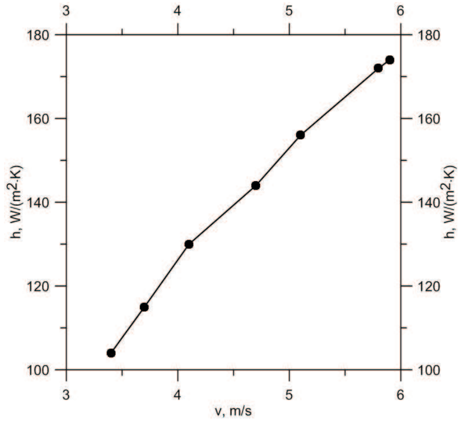

Figure 7. The heat transfer coefficient as a function of the flue gas velocity.

4 Conclusions

The heat transfer coefficient in the fluidized bed is strongly dependent on flue gas temperature and flue gas velocity, as well as on the concentration and velocity of solid particles. Therefore precise measurement data are needed for its determination. The results obtained in this work present the changes in the heat transfer coefficient on the flue gas side of platen superheater located in the upper part of the furnace of a CFB boiler, where the concentration of solids is relatively low. The values of heat transfer coefficients were obtained from CFD simulation in steady-state. In the proposed method, the heat transfer coefficient was determined based on the increase of the steam temperature flowing through the platen superheater. The presented approach to determine the heat transfer coefficient based on numerical simulation can be used to design and operate the boiler. All of the necessary data, such as the mass flow, temperature, and pressure of the steam as well as the temperature of the flue gas, were measured during the boiler operation at different loads. The flue gas-side heat transfer coefficients determined can be used in the design and operation of CFB boilers.

Received in August 2012

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Modelowanie grodziowych przegrzewaczy pary dla różnych obciążeń w kotle z cyrkulacyjnym złożem fluidalnym

S t r e s z c z e n i e

Przegrzewacz pary drugiego stopnia jest to przegrzewacz grodziowy wykonany z rur „podwójna omega”. Przegrzewacz jako wymiennik ciepła, zbudowany jest z trzech biegów. Każdy bieg jest wykonany z innego gatunku stali niskostopowej. W artykule przedstawiono obliczenia rozkładu temperatur pary, jak również ścianki rury grodziowego przegrzewacza, dla różnych obciążeń kotła z cyrkulacyjnym złożem fluidalnym (CFB).