Correlations for Pollution on Condensing Surfaces of Exhaust Gas Boilers with Water-Fuel Emulsion Combustion

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Abstract. The absence of reliable methods for calculating heat transfer of condensing water vapor from exhaust steam-gas mixtures with a high content of non-condensable gases on the surface of a pollution layer in the exhaust gas boilers with water-fuel emulsion (WFE) combustion needs theoretical and experimental studies. Experimental researches of pollution intensity at wall temperatures below dew point of sulfuric acid vapors were carried out on the experimental setup with combustion of fuel oils and WFE. Based on the experimental-theoretical data the correlations for dependence of pollution coefficient of WFE, wall temperature, gas speed, pipe diameter and pipe steps have been developed. The regression equation makes it possible to estimate the influence of various factors such as water content of WFE, wall temperature and gas speed on pollution coefficient. Analysis of the research results has shown that WFE combustion with water content of 30% reduces the level of pollution coefficient of heating surfaces and increases the cleaning periodicity. The obtained values of pollution coefficients can be used in the design and operation of condensing heating surfaces of boilers.

Keywords: Low-Temperature Heating Surfaces · Exhaust gases · Fuel oil

1 Introduction

An exhaust gas boiler (EGB) is the main waste heat recovery equipment that influences considerably on the efficiency of any thermal power plant from cogenerative internal combustion engines and gas turbines [1, 2] to trigenerative plants generating power, heat and cooling (refrigeration and air conditioning) [3–5], i.e. practically in all waste heat recovery technics [6, 7]. Using of condensing low-temperature heating surfaces (LTHS) in EGB allows to increase the economic efficiency and environmental performance of boilers and thermal power plants in the whole. When fuel oil is burnt, the intensity of low-temperature corrosion (LTC) increases to 1.2 mm/year at wall

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temperatures above 130 °C. The pollution intensity increases, too. In the case of water-fuel emulsions (WFE) combusted with water content of $W^r = 30\%$ [8, 9] or injection water in combustion chamber [10], there is a significant decrease of LTC intensity to the level 0.25 mm/year, due to the passivation of the metal [11, 12] under a thin layer of sulfuric acid condensate by absorbed nitrogen oxides. That makes it possible to install condensing LTHS at a wall temperature t_w below the dew point temperature of sulfuric acid vapors and, consequently, provides possibility to use heat of condensing vapors of H_2O and H_2SO_4 at t_w until 65…70 °C within high working reliability of these condensing LTHS. The best burning out of fuel combustible components due to applying a WFE provides decreasing a concentration of solids and soot in the exhaust gases and hence their toxicity [13, 14] and pollution layer [15].

2 Literature Review

Many studies focus on the reuse of exhaust gases for cogeneration [16] and the use of this energy for pre-drying in coal power plants, which increases the thermal efficiency of the system by approximately 2% [17]. Zhang et al. [18] presented the idea of reducing the flue gas temperature below the dew point of the water vapor within it to simultaneously recover latent heat and obtain clean water. The heat transfer mode of this method is a direct contact mode that utilizes the flue gas desulfurization scrubber as a flue gas water vapor condensing heat exchanger. Similarly, Bilirgen et al. [19] developed an analytical model for a flue gas condensing heat exchanger system to predict the heat transferred from the flue gas to the cooling water and the water vapor condensation rate in the flue gas. Considering the actual concern for reducing the fuel consumption along with pollution reduction, the condensing boilers get a major importance for the manufacturers. In the context, more and more small boilers producers shift their non-condensing units to condensing units. Because of economical constraints linked to manufacturing costs it is of outmost importance for the producers to study a range of constructive solutions in the design stage [20]. The numerical and computational modeling of a boiler made out of packages of finned tubes and packages of smooth pipes is presented in the paper [21].

The presence of deposits on heat exchange surfaces in condensers and regenerative exchangers of ship and land steam power plants is always connected with the increase of the wall temperature due to additional thermal resistances resulting from accumulated deposits. In the article [22], based on the results of the author's own experimental research, the types of pollution accumulating on heat exchange surfaces on the water vapor side of heat exchange apparatus in marine and land steam power plants and quantitative measures of the unevenness of the surface layer of these deposits are presented.

Energy extraction beyond the dew point of the moisture present within the flue gas are quite attractive. In study [23], a novel waste heat and water recovery system composed of an organic Rankine cycle and cooling cycles using singular working fluid accompanied by phase change was proposed and optimized for maximum power output. Heat exchangers, which cool boiler flue gas to temperatures below the water vapor dew point, can be used to capture moisture from flue gas and reduce external water consumption for power plant operations [24]. At the same time, thermal energy removed from the flue gas can be used to improve unit heat rate. Recent data also show that emissions of air toxics from flue gas would be reduced by use of condensing heat exchangers [25]. A set of fault detection and diagnosis tools for dynamic energy efficiency monitoring and assessment in condensing boilers is developed in works [26, 27].

When conducting heat-engineering calculations of LTHS during combustion of liquid fuels and WFE based on them, it is necessary to know the values of the thermal resistance of the pollutions on the dry surfaces and condensing LTHS. For dry convective heating surfaces, the values of ε_p are received in accordance with [28, 29]. The normative method [28] recommends, with excess air factor α above 1,03, to take the value $\varepsilon_p = 0.005\ m^2$ K/W for dry LTHS during combustion fuel oil, regardless of the gas velocity w_g, wall temperature t_w and water content in fuel oil W^r. For condensing LTHS during combustion of fuel oil and WFE, recommendations on the choice of the values of ε_p are not presented in publications.

Analysis literary sources showed there are no data on the values of the pollution coefficients for both condensing and dry heating surfaces with WFE combustion.

The aim of research is to obtain the correlations for dependence of the pollution coefficients (thermal resistance) of the layer of pollution on the wall temperature t_w, gas velocity w_g, water content of WFE W^r based on sulfurous fuel oil for dry and condensing heating surfaces. The research tasks are:

- studying of influence of wall temperatures t_w, gas speed w_g and water content of WFE W^r on the value of pollution coefficient ε_p for dry and condensing heating surfaces;
- obtaining the regression equation of influence of various factors such as water content of the WFE W^r, gas speed w_g and wall temperature t_w on pollution coefficient;
- determining the cleaning periodicity dry and condensation heating surfaces.

3 Research Methodology

The absence of reliable methods for calculating heat transfer under conditions of condensation of water vapor from steam-gas mixtures with a high content of non-condensable gases on the surface of a pollution layer requires theoretical and experimental studies. Experimental researches of pollution intensity at wall temperature values below dew point temperature of sulfuric acid vapors were carried out in an experimental setup with combustion of fuel oils and WFE based on them [15].

Based on the conduct experimental and theoretical researches with fuel oil and WFE based on them combustion [15], the correlations of pollution average thickness δ and coefficient of equivalent thermal conductivity λ were obtained as a function of the wall temperature. It made possible to develop the correlations of the pollution coefficients $\varepsilon_p = \delta/\lambda$ on the wall temperature $\varepsilon_p = f(t_w)$ at the time of gas flow impact $\tau = 1000$ h (Fig. 1).

When carrying out thermal calculations of LTHS, it is necessary to carry out zone calculations: for the vapor-liquid zone ($t_w = 120\ldots140$ °C) the variable values ε_p from

t_w should be taken (Fig. 1); in the ranges of t_w equal to 120 °C and below (up to 70 °C) (condensation surfaces) and t_w equal to 140 °C and above (up to 240 °C) (dry surfaces), constant values of ε_p should be taken depending on the water content level (shown in Fig. 1 in dotted lines). As can be seen from the graphical correlations presented in Fig. 1 in the zone t_w = 120…140 °C a sharp increase of ε_p values is observed.

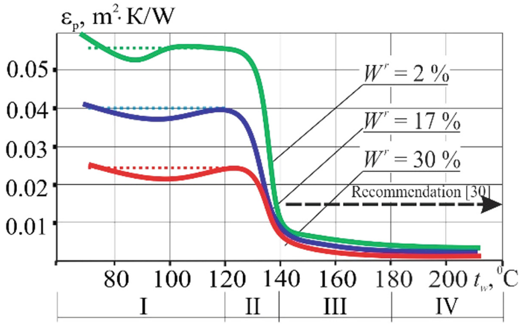

Fig. 1. Correlations for dependence of pollution coefficient ε_p on wall temperature t_w during combustion fuel oil and WFE based on them (at zones of heating surfaces EGB): I – condensing surface, II – economizer, III – evaporator, IV – superheater.

For estimating the adequacy of the research results ε_p, values obtained for dry LTHS (III, IV zones) were compared with recommended [28]. It should be noted that obtained ε_p values for fuel oil coincide with recommended in [28] values.

Based on experimental and theoretical researches the dependence of pollution coefficient ε_p values on the wall temperatures t_w, gas speed w_g and water content of WFE W^r, pipe diameter and pipe steps were obtained.

For evaluation of the joint effect of three factors (t_w, w_g, W^r) on the pollution coefficient ε_p, determination of the values of constants and weight coefficients in the equation of multifactorial regression, the Statgraphics Plus for Windows system, providing access to a full set of statistical methods and providing an opportunity to conduct an extended regression analysis was used. Determination coefficients in all presented equations are found on level 0.96…0.99.

4 Results

The carried out experimental-theoretical researches of pollution kinetics allowed to obtain correlations for vapor-liquid zone:

– pollution coefficient ε_p from wall temperature t_w

$$\varepsilon_p = f(t_w), \tag{1}$$

– pollution coefficient ε_p from gas speed w_g

$$\varepsilon_p = f(w_g), \tag{2}$$

– pollution coefficient ε_p from water content W^r

$$\varepsilon_p = f(W^r). \tag{3}$$

The correlations in Fig. 2 are received at w_g = 8 m/s and show an increase of ε_p with rising wall temperature t_w. When fuel was combusted at W^r = 2% with an increase of t_w from 120 to 140 °C, the value of ε_p increased by 4.3 times, when WFE was combusted at W^r = 17% - by 4.4 times, at W^r = 30% - by 3.6 times. At t_w = 130 °C, an increase in the water content of the WFE from 2 to 30% leads to decrease of ε_p by 2 times.

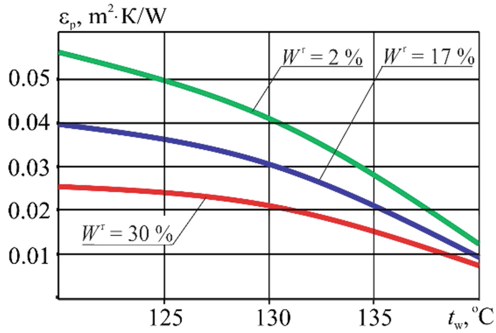

Fig. 2. Correlations for dependence of pollution coefficient ε_p on wall temperature t_w at different water content W^r WFE (w_g = 8 m/s).

There were obtained correlations for dependence of ε_p on gas speed w_g (Fig. 3) and water content of emulsion W^r (Fig. 4) for condensing (t_w below 120 °C) and dry (t_w above 140 °C) heating surface.

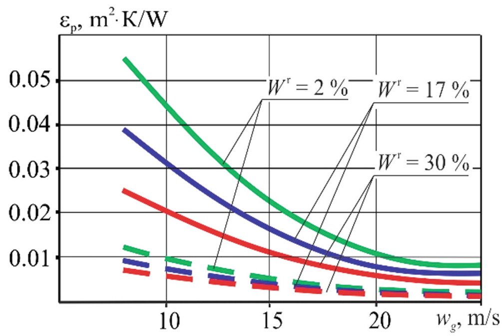

Fig. 3. Correlations for dependence of pollution coefficient ε_p on of gas speed w_g at different water content W^r WFE: —— − t_w = 120 °C; – – – − t_w = 140 °C.

At fuel oil and WFE combustion within increase of water content WFE from 2 to 30% the value of ε_p for dry heating surface decreases in 1,5 times; within increase of gas speed from 8 till 25 m/s - in 6 times. At fuel oil and WFE combustion within increase of water content WFE from 2 to 30% the value of ε_p for condensing heating surface decreases in 2.2 times; within increase of gas speed from 8 till 25 m/s – in 6.8 times.

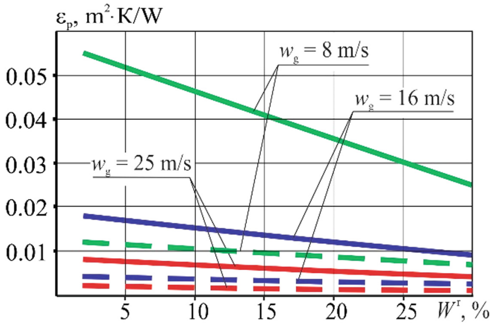

Fig. 4. Correlations for dependence of pollution coefficient ε_p on water content W^r WFE within different gas speed w_g: —— − t_w = 120 °C; – – – − t_w = 140 °C.

The statistical data processing made it possible to obtain equation for the vapor-liquid zone of LTHS at combustion fuel oil and WFE, taking into account influence of wall temperatures t_w, gases speeds w_g and water content of WFE W^r on the value of pollution coefficient in the form:

$$\varepsilon_p = \left(207.419 - 0.1797t_w - 3.6845W^r - 11.3073w_g + 0.0226t_w W^r\right) \cdot 10^{-3} \quad (4)$$

Equation gives the values of ε_p in the range of magnitudes: t_w = 120…140 °C, W^r = 2…30%, w_g = 8…25 m/s.

Experimental-theoretical data on the effect of pipe diameter and pipe steps on the magnitude of the pollution coefficient are shown in Figs. 5 and 6.

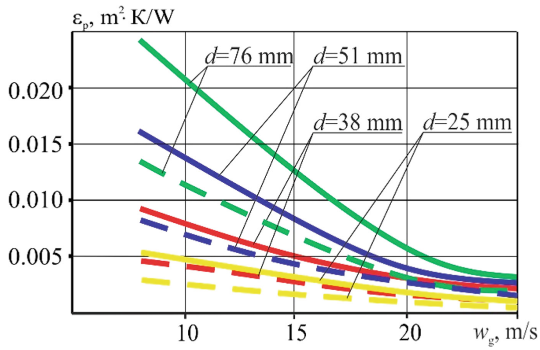

Fig. 5. Correlations for dependence of pollution coefficient ε_p on gas speed w_g within different pipe diameter (s_2/d = 2, τ = 8 h, t_w = 130 °C): —— − W^r = 2%; – – – − W^r = 30%.

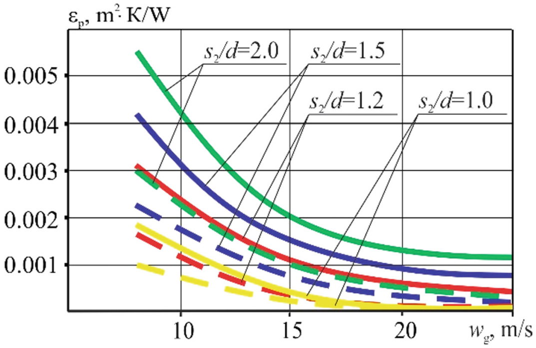

Fig. 6. Correlations for dependence of pollution coefficient ε_p on gas speed w_g within different pipe steps s_2/d (d = 25 mm, τ = 8 h, t_w = 130 °C): —— − W^r = 2%; - - - − W^r = 30%.

The graphs show a very strong dependence of the pollution coefficient ε_p on the pipe diameter. So, with a decrease in diameter from 76 to 25 mm for a chess arrangement, the value of ε_p decreases in average by 5 times, and with a decrease from 38 to 25 mm - by 2 times.

As experience shows, during the transition to small diameters, the similarity of the pollutant layer is not fully observed, and the decrease in the thickness of the pollutant layer is more significant than the decrease in diameter.

According to the relation results [15] and values $\varepsilon_p = f(\tau)$ values of periodic cleaning for dry and condensing surfaces (Figs. 7, 8) were obtained while fuel oil and WFE combustion.

The results of calculations of ε_p at a wall temperature of 110 °C (in the region of the "acid peak") show that with an increase water content of WFE up to 30% due to a decrease in the concentration of solid particles (one of the pollution components) by 3 times, a decrease in the corrosion rate by 3…5 times, which determines the thickness of the sulfate layer, the decrease in the thickness of pollution (by bulk density) is almost 4 times and increases the period between heating surfaces cleaning.

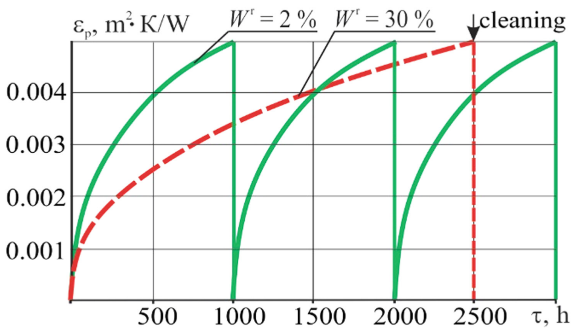

Fig. 7. Correlations for dependence of cleaning periodicity while reaching equal pollution coefficient for dry heating surface.

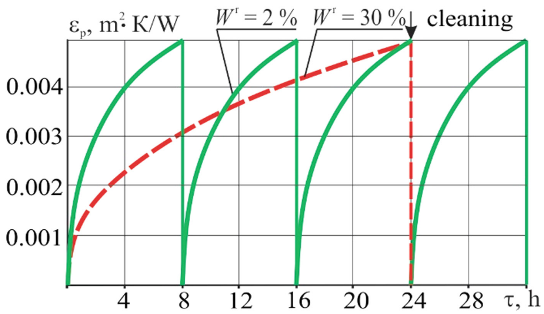

Fig. 8. Correlations for dependence of cleaning periodicity while reaching equal pollution coefficient for condensing heating surface.

The obtained approximating equations of pollution for condensing LTHS give the opportunity to determine the frequency of intensive cleaning (according to Figs. 7, 8), for example, by washing, determined by the exposure time value of the flue gas flow at which the same pollution coefficient ε_p is reached, equal to 0,005 m^2/K W. It was assumed that under different fuel combustion conditions all deposits are removed up to the sulfate layer. The growth of the sulfate layer is determined by the corrosion rate taking into account the ratios of iron valency.

The results of computational studies showed that during the transition to burning WFE with W^r = 30%, the cleaning periodicity of dry surfaces increases from 1000 h at W^r = 2% to 2500 h at W^r = 30% (Fig. 7). The cleaning periodicity of condensing surfaces increases from 8 h at W^r = 2% to 24 h at W^r = 30% while ensuring reliable operation of EGB heating surfaces (Fig. 8).

5 Conclusions

Analysis literary sources showed there are no data on the values of the pollution coefficients for both condensing and dry heating surfaces with WFE combustion.

The correlations for dependences of the pollution coefficient upon water content of WFE, gas speed, wall temperature, pipe diameter and pipe steps with wall temperatures below dew point temperature of sulfuric acid pair have been developed on the base of experimental-theoretical data.

The regression equation has been obtained that makes it possible to estimate the influence of water content of the WFE, gas speed and wall temperature on pollution coefficient. Obtained relations and regression equation $\varepsilon_p = f(t_w, W^r, w_g)$ are useful for designing the condensing heating surfaces EGB.

The values obtained for dry cleaning periodicity and condensing heating surfaces can be used to develop recommendations for their operation.

The work considers only one of the aspects of problem - the pollution intensity of condensing heating surfaces of EGB when heavy fuels and WFE based on them combustion in ICE. Research in this direction can be continued. We see the prospects for further study of the problem in a more detailed study of the impact of WFE spray quality on the pollution intensity of condensing heating surfaces.

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