FOULING AND HEAT TRANSFER IN A FURNACE UNDER VARIABLE LOAD OF A LIQUID SLAG REMOVAL BOILER

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The physical parameters that characterize the fouling dynamics of the water wall surfaces of the chamber furnace when its heat load varies are determined. The effect of the variable heat transfer conditions in the furnace on the working surface of steam generating tubes is substantiated.

Introduction. The growth of the role of coal as a fuel for steam power plants makes it necessary to solve the problem of how to substantially improve its use in traditional and new burning technologies. However, solving the problem becomes complicated because of the variable operating conditions of boiler equipment. Systematically, the greater part of the equipment is used to regulate the load schedule by deep discharges or stops. These operating conditions are realized for unstable quality characteristics of burnt coals that require their use in combination with other organic fuels. The boiler service conditions other than the designing ones greatly affect the fouling and heat transfer from chamber furnaces, especially, from liquid slag removal ones. Their service experience points to a noticeable growth in the number of damaged deflecting walls due to their local superheating and hydrogen absorption by metals. And at the same time, complete theoretical resolutions of these problems are absent, and the design methods are restricted to steady-state conditions; therefore, reliable operation of variable load boilers is determined by the staff of electric power plants, taking as a basis their own experience. In this regard, some methodological aspects of the problem, given below, and the design characteristics of the transient operating conditions of liquid slag removal furnaces may be of interest.

The steady-state operating conditions of a liquid slag removal furnace are typical of permanent fouling of its active zone (refractory-faced and concrete sprayed), which is provided by the dynamic equilibrium between the amount of ash put on the surface and the liquid slag falling down. When the boiler heat load varies, the fouling conditions become variable. In particular, upon discharge the slag film becomes thinner or completely disappears. The amount of the ash put on the surface exceeds that of the liquid slag falling down, and the slag coating thickness grows, thereby "encasing" the furnace chamber for warmth-keeping. This transient process occurs for several hours and is ended in a new steady-state characterized by the condition $d\delta_{sl}/d\tau = 0$.

By using the design model, it is possible to determine the behavior of the slag film thickness and slag crust at varying furnace heat loads. The dynamics of the furnace slag coating is described here according to [1]:

$$\frac{d\delta_{sl}}{d\tau} = \frac{BA^{p}\bar{\eta}_{sl}}{\rho_{sl} H_{r.h.}} - \frac{\rho_{sl}\delta_f^3}{LM_0\left(\ln\frac{\mu_0}{\mu_{slf}}\right)^3}\left[\frac{S_{slf}}{\rho_{sl} S_f}\ln\frac{\mu_0}{\mu_{slf}} \times \right.$$

$$\left. \times\left(\frac{\mu_0}{\mu_{slf}} - \ln\frac{\mu_0}{\mu_{slf}} - 1\right) + 2\left(\frac{\mu_0}{\mu_{slf}} - 1\right) - 2\ln\frac{\mu_0}{\mu_{slf}} - \left(\ln\frac{\mu_0}{\mu_{slf}}\right)^2\right].$$

The values of the parameters δ_f, δ_{cr}, $T_{sl.f.}$ characteristic of the steady-state fouling conditions are taken as the initial conditions to solve the equation. The experimental relation [2] $\eta_{sl.} = f(T_{sl.f.})$ is used to calculate the slag trapping coefficient $\eta_{sl.mean}$ of the combustion chamber. In calculations the fact is taken into account that the true liquid slag temperature, the burnt oil fraction, and the flame temperature are affected by the burnt coal quality and by the coal dust milling fineness [3, 4].

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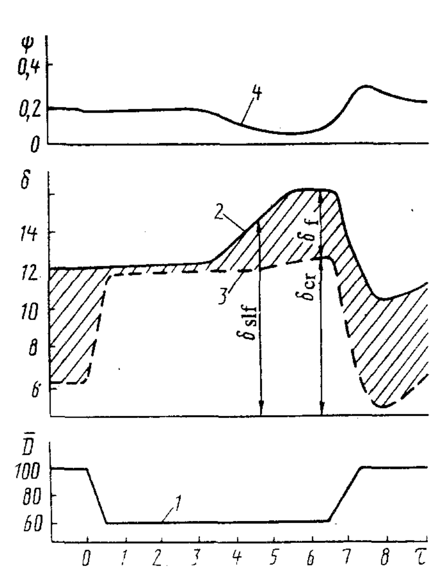

Fig. 1

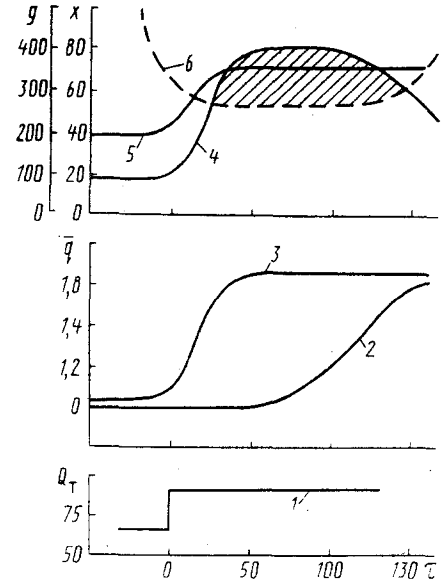

Fig. 2

Fig. 1. Dynamics of the slag coating thickness and the deflecting wall thermal efficiency in the active zone of the TP-100 boiler furnace (under the Russian trademark): 1) steam boiler load curve; 2) total slag coating thickness; 3) slag rust thickness; 4) thermal efficiency of water walls. $\bar{D}$, %; δ, mm; τ_0, h.

Fig. 2. Heat transfer parameters over the water wall tube section adjacent to the active furnace zone: 1) boiler heat load curve; 2) relative heat load of the refractory-faced tube; 3) the same, adjacent to the smooth tube section; 4) local steam content in the adjacent tube; 5) absolute level of the absorbed heat flux; 6) critical heat flux. g, kW/m^2; x, $Q_{fur.}$, %.

From Figure 1 it is seen that in the active zone of the TP-100 boiler furnace the thickness and structure of the slag coating (curves 2, 3) greatly decrease in the furnace chamber upon reducing the heat load (curve 1). Before discharge the total thickness of the slag crust and the film is 12.5 mm. In this case, the slag crust thickness (curve 3) is equal to 6.4 mm and that of the slag film (hatched region) is 6.1 mm. After 40 min discharging of the boiler by 40% (200-120 MW) the slag film thickness practically becomes equal to zero, and the slag crust thickness is increased by the initial thickness of the slag film. Further, for 2-3 h the slag coating slowly grows due to increasing slag crust thickness. After the first stabilization stage comes to an end, when the slag coating surface temperature becomes equal to the true liquid slag one, the second stage starts, implying that the slag film thickness appears and grows intensively. To the end of this stage it is stabilized at a level of 3.8 mm (Fig. 1). Thus, at the decreased load the furnace itself is encased for warmth-keeping.

At the boiler load the transient process mechanism is reversed. A considerable thermal resistance of the ash-slag deposits piled up during the discharge promotes an excess of the nominal temperature level in the furnace chamber. In this case, the slag film becomes more thick and is superheated, and is followed by an increase in the rate of its falling down. Due to the inertia of this process the slag coating thickness becomes less than the nominal one at a certain discharging stage.

The unstable thermal efficiency of screens $\psi(\tau)$ $q_{ab}(\tau)/q_{in}(\tau)$ (Fig. 1, curve 4) corresponds to the variable conditions of the active zone fouling. The instability of the coefficient $\psi(\tau)$ is the cause of the heat transfer unsteadiness within the transient process. In this situation, upon discharge q_{in} is mainly variable in the active zone. In virtue of the interdependency relation and agreement between varying indices of q_{in} and ψ, the quantity q_{ab} practically does not respond to the variable fouling conditions and is determined by the furnace heat load alone.

The fouling dynamics of the active furnace zone exerts a determining influence on the operating conditions of the nonrefractory-faced sections of the deflecting walls located above this zone. The quantity ψ in them varies inconsiderably during the transient process. Moreover, the incident heat fluxes, especially during loading, grow due to the increase of the furnace temperature level. Therefore, here q_{ab} responds to the increasing heat load and to the reconstructing structure of the slag coating of the active zone. Practically, this results in a 25-30% excess of the nominal level of q_{ab} above the active zone during loading and, as a consequence, in an increase of the temperature level of the metal of the tubes of the deflecting walls, as well as in its hydrogeneration [5].

There are prerequisites to consider, such as that the tube metal reliability is affected not only by the absolute level of the absorbed heat flux but also by the rate of its variation, whose values are essential at boiler load (Fig. 2, curves 1, 2). The above prerequisites are based on a comparative analysis of the dynamics of heat transfer parameters in the furnace (q_{ab}, $T_{fl.}$) and of the medium circulation parameters in a deflecting wall system. As statistical analysis shows, in practice the ruptures of the tubes of the deflecting walls mainly occur over the tube sections close to the refractory-faced zone of the furnace, on upper aerodynamic protrusion boilers and in the protrusion zone.

Consider the operating conditions of the above tube sections during loading of a liquid slag removal boiler. As mentioned, with increasing the heat supply to the furnace chamber encased for warmth-keeping, the incident heat flux grows. If at loading the kind of burnt fuel changes, then the q_{in} growth is 40-60% [2]. The absorbed heat flux grows in proportion and reaches the surface of smooth-tube deflecting walls with a minimal time delay.

As is known, the circulation velocity of a working medium in the deflecting wall tubes and its other parameters are, to a considerable extent, determined by the mean steam content level along the entire heated tubes. Therefore, the temperature and heat transfer regimes over the sections of the tubes adjacent to the active furnace zone greatly depend on the heat transfer dynamics in the active furnace zone. Under these conditions the inertia of heat transfer processes in this zone is of significance.

Figure 2 is useful for understanding the physical model of the process under study. Here the parameters of boiler loading that are most dynamic and, accordingly, most heat-stressed are presented. Its main distinctive feature lies in the fact that over different sections of the deflecting wall tubes the moments of intensive heat load growth do not coincide in time. The noncoincidence value reaches 70-100 sec and is determined by the inertia of the slag concrete-sprayed coating of the active zone. As a result of the above noncoincidence the local steam content increases in the neighboring sections of the tubes, and the local level of the critical heat flux determining the first-kind heat transfer crisis decreases there [6]. Despite the absence of conditions for this phenomenon in the integral respect, the probability of its local manifestation is essential: it increases with increasing absolute value of the heat load and, especially, the rate of its variation. The heat transfer crisis may be observed in microvolumes near the heated tube surface. Its manifestation time is determined from the medium circulation reconstruction time in the deflecting wall system.

Experimental study of the mentioned phenomenon is difficult; therefore, the calculation data are of interest. The mathematical model for the process is a system of equations describing heat transfer in the furnace chamber at unsteady heat load [7]. To describe circulation and heat transfer inside a tube, equations for the steady-state operating conditions [8] are used, which are supplemented with equations allowing for the variable steam content along the transverse flow coordinate of the steam generating tube, and with the equation for the critical heat flux vs performance parameters, etc.

The extreme values of the local steam content in steam generating tubes from the furnace side are shown in Fig. 2. As is seen, the critical heat flux levels corresponding to them can reduce to real values in these cases, especially when their mentioned increase in transient processes is taken into account.

Indirect data pointing to systematic violations of the normal heat transfer conditions in steam generating tubes of boilers that participate in regulating the heat load are obtained on the TP-100 boilers. Experimentally, the excess of the metal temperature of the tube sections close to the active furnace zone is fixed by 30-60°C against the design one. The maximum incident heat flux during boiler loading is 520-580 kW/m^2. The rate of varying the absorbed heat flux attains 33 kW/(m^2·min). Because of the hydrogen embrittlement of metal the number of tube ruptures in this zone reaches tens per year.

Analysis of the design model shows that in the aerodynamic boiler protrusion zone, the violation of heat transfer conditions from the working medium side can be the cause of the two-phase flow disintegration inside the tubes despite relatively moderate absolute values of the incident heat fluxes and the rate of their variation.

Conclusion. The unsteady operating conditions (decreased load, variation of the air conditions, burner changing, etc.), which are allowed for at present when designing furnaces with liquid slag removal, are insufficient to provide reliable operation of boiler units. Attention must be paid to transient processes in liquid slag removal furnaces that accompany the variation of their heat load.

Use of the variable thermal efficiency coefficient of the deflecting walls for designing dynamic furnace characteristics, as well as for designing the dynamics of the local steam content in steam generating tubes of the deflecting walls, will allow one to exclude extremal or close to extremal operating conditions of boilers from the service practice. At present this problem is being solved experimentally. In this case, large-scale damages of the deflecting wall tubes are, for example, a criterion which specifies the necessity of setting a limit on the boiler loading rate. In particular, such a situation has occurred on the TP-43 boilers (under the Russian trademark) of the Lugansk Hydroelectric Power Station.

The physical and mathematical models for the transient processes in furnaces used in calculations permit one to develop engineering methods of calculating the safe operation of liquid slag removal boilers when the latter are intensively utilized to regulate the variable component of the electric power plant load chart.

NOTATION

B, fuel flow rate, kg/sec; A^P, fractional ash content of the working fuel mass; $\eta_{sl.mean}$, mean slag trapping coefficient in the furnace combustion chamber; L, combustion chamber perimeter, m; S_f, stress function in a film, P·sec; μ_0, dynamic slag viscosity at a true liquid state, P·sec; δ_f, δ_{cr}, thickness of the slag film and crust, respectively, m; $\delta_{sl.}$, total slag coating thickness, m; τ, time, sec; $\mu_{sl.f.}$, dynamic slag viscosity at a true film temperature, P·sec; $\rho_{sl.}$, slag density, kg/m^3; $H_{r.h.}$, radiant heat absorbing furnace surface, m^2; sl.f., slag and incident heat fluxes, kW/m^2; ψ, thermal efficiency of walls.

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