Effect of Atmospheric Smoke and Slag Height on Heat Exchange in ARC Steel Smelting Furnaces. Part I. Effect of Atmospheric Smoke on Losses with Gases and Water

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Abstract
The composition of the dust and gas atmosphere affects the heat transfer in the arc steelmaking furnace. With a significant dust content of the furnace atmosphere, the heat flux of arcs emitted by them into the free, not filled with charge, space is mainly absorbed by the dust-gas medium and carried away from the furnace in the form of heat losses with exhaust gases. In the radiant atmosphere of the furnace, the heat flux of the arcs, radiated by them into the free space, reaches the walls, is absorbed by the water of the water-cooled panels and is carried away from the furnace in the form of heat losses with the cooling water.

Keywords: Electric steel, electric arc, heat exchange, thermal radiation, furnace.

1) INTRODUCTION
Currently, in the world and in Russia, up to 40% of steel is produced in electric steel smelters (Figure 1) in arc steel smelting furnaces (ASF). Throughout the 20th century, there was no methodology for calculating heat exchange in the ASF. At the end of the 20th, beginning of the 21st centuries, the Tver State Technical University developed the theory of heat exchange in ASF [1]. We will use the developed theory and method of calculating heat exchange in the ASF to analyze the effect of the composition of the dust-gas atmosphere and the height of the slag layer on heat exchange and specific consumption of electricity in the ASF. Electric arcs are the main sources of energy in arc steelmaking furnaces (Figure 2).

Figure 1. Electric steelmaking plant in a steel company in China, with a capacity of 6 million tons of steel per year
From these energy balances of steel melts in ASF [2], arcs account for 55-65% of the energy, from gas-oxygen burners (GOB), exothermic oxidation reactions of iron and other elements of the charge 35-45% of the energy supplied to a modern high-power ASF. All electrical energy in ASF is converted into heat energy. According to numerous experimental studies of heat transfer carried out by several groups of researchers for 10 years on arc steel-making furnaces of a whole range of capacities from 3 to 200 tons, the heat flux of ASF arcs consists of 92-96% of the heat radiation flux, 4-8% of the convective flux, and the flow transmitted by thermal conductivity [3-7]. Let us analyze the influence of the height of the slag layer and the smoke content of the atmosphere on heat transfer and specific power consumption in modern high-power arc steel smelting furnaces ASF-100, ASF-120, ASF-150, with a capacity of 100, 120, 150 tons, respectively. The compared furnaces operate both on scrap and on metallized pellets with charge loading with loading baskets and a loading conveyor with heated charge. All modern methods of intensifying the steel melting process are used in the furnaces: GOB, coal powder injectors, oxygen tuyeres, automated production process control systems. The compared furnaces operate in the same energy modes and have the following indicators [8, 9]: specific power of the transformer 700-800 kVA/t; oxygen consumption 20-30 m³/t; natural gas 5-10 m³/t; coal 5-15 kg/t; melting time 45-60 minutes; specific power consumption 375-440 kW·h/t (when melting pellets and scrap, specific power consumption 530-550 kW·h/t).

2. THERMAL LOSSES IN ASF WITH EXHAUST GASES AND COOLING WATER

Specific losses with exhaust gases in furnaces ASF-100-ASF-150 vary from the maximum value of 242 kW-h/t in ASF-120 Consteel with conveyor loading of the heated charge with exhaust gases, which is 31% of the consumable part of the energy balance, to a minimum value of 140 kW-h/t (22% of the consumable part of the energy balance) in ASF-120 from the loading charge in baskets. Greater dust and gas production in the ASF-120 Consteel furnace compared to the ASF-120 of conventional design is explained by the use of 65% large mass of coke powder in Consteel to maintain the foamy slag throughout the melting process and increase the efficiency of arcs to 0.73-0.6 [2]. Arcs in Consteel furnaces burn on the metal bath all the time, and they must be constantly shielded with slag to increase the share of the thermal radiation power of the arcs on the metal bath and slag, and reduce the share of the thermal radiation power of the arcs on the walls and roof of the furnace.

In ASF-120 furnaces of conventional design, it is not necessary to induce slag part of the melting time, since after filling the charge and cutting the wells, the arcs burn in the wells, are shielded by wells and usefully radiate 93-80% of the arc power to the metal bath and metal charge in the wells. The efficiency of arcs in ASF-120 in the above-described period is 0.93-0.80 [2]. The maximum value of specific losses with exhaust gases of 242 kW-h/t in ASF-120 Consteel corresponds to the minimum value of losses with cooling water in these furnaces of 48 kW-h/t, which is 7% of the consumption part of the energy balance. In the energy balance of ASF-120 with loading the charge with baskets, the minimum value of specific losses with exhaust gases of 140 kW-h/t corresponds to the maximum value of losses with cooling water, which is 50-60 kW-h/t or 8-9% of the consumption part of the energy balance. From the analysis of the energy balances of ASF-100-ASF-150, the following dependencies can be traced: the greater the consumption of oxygen and coal powder in the melting process, the greater the volume of waste gases, the greater the heat loss with the exhaust gases and the lower the heat loss with the cooling water. The furnaces operate in similar energy modes, with similar specific power of the arcs, water is used to cool the wall panels and the roof of the furnaces.

The dust-gas atmosphere of the furnace is a suspension of solid and liquid particles in a gaseous medium. The particle board gas medium consists of nitrogen, oxides and dioxides of nitrogen, oxygen, oxides and carbon dioxide. Dust consisting of Fe₂O₃, SiO₂, Al₂O₃, CaO, MgO, MnO is suspended in a gaseous medium.
Dust content of ASF gases depends on the melting period and varies from 5 to 50 g/m$^3$ [10], that is, it changes 10 times during the melting process. The maximum value of 40-50 g/m$^3$ dust content of gases reaches during the period of purging the bath with oxygen or feeding powdered carbon into the ASF. The size of dust particles is in the range from 0.01 to 100 μm [11]. The temperature of the vapor-gas mixture at the outlet of the furnace changes during the melting process in a wide range from 300–600 °С during the melting of the charge to 1500–1600 °С during the period of intensive oxygen purging of the bath. The density of electric arc furnace dust is 0.9 t/m$^3$ [10].

With a significant change in the process of melting the dust content of the dust-gas mixture from 5 to 50 g/m$^3$, the size of the dust from 0.01 to 100 microns, the absorption coefficient of the dust-gas atmosphere of the furnace varies within the range $k = 0–1.4$ [1,2]. In the calculations of heat transfer in the chipboard, we used the absorption coefficient $k = 0.1$ for the radiant furnace atmosphere and the average absorption coefficient $k = 0.7$ for the dusty atmosphere of the furnace, while satisfactory agreement was obtained between the experimental and calculated data of heat transfer in the chipboard with a water-cooled roof and walls [1, 2]. With the absorption coefficient of the dust-gas atmosphere of the furnace $k = 0.7$, calculations and measurements obtained similar in magnitude (difference by 10 - 20%) thermal loads on the water-cooled panels of the walls and vault [1].

3. METHOD OF CALCULATION OF THERMAL RADIATION FLUXES OF ARCS ON THE WALLS OF ASF

We will find out the influence of the volume of gases leaving the furnaces and the height of the slag layer on the thermal loads on the water-cooled wall panels and heat flows with cooling water. Figure 3 shows the necessary constructions for calculations performed at scale in the AutoCAD and Excel programs. Symbols used in Fig. 3: $h_{st}$ – the height of the ASF walls, m; $d_e$ – the diameter of the electrode, m; $h_a, h_m, h_s$ – the height of the arc depth, respectively, total, in metal, in slag, m; γ – the angle formed by the horizontal plane of the end of the electrode and the inclined plane that occurs on the electrode due to the electrodynamic movement of the arc from the axis of the electrode to its periphery, deg.; $0...5$ – the calculated points on the walls of the furnaces; $l_a$ – the length of the arc, m; $l_{opa}$ – the length of the open part of the arc radiating heat flow to the calculated site, m; $r$ – the beam, the distance from the arc to the calculated point on the walls, m; α – the angle between the beam $r$ from the middle of the open part of the arc and the perpendicular $N_1$ to the arc axis drawn at the beginning of the ray $r$ on the arc, deg.; β is the angle between the normal $N_2$ to the wall surface at the calculated point and the ray $r$, deg.; θ is the angle of the electrodynamic deviation of the arc axis from the electrode axis, determined by the method described in [1].

![Diagram](image-url)
The density of the flux of thermal radiation from the arc $q$, incident on the calculated area located on the walls of the chipboard, was determined by Makarov's first law of thermal radiation from gas volumes [1]:

$$q = \frac{\alpha_{ac} P_a \cos \alpha \cos \beta l_{opa}}{\pi r^2 l_a} e^{-kr}$$

where $\alpha_{ac}$ is the fraction of the arc power, which stands out in the arc column, is determined by the method described in [1]; $P_a$ - arc power, kW; $k$ - absorption coefficient of the gas atmosphere of the furnace, varies in ASF in the range from 0.1 to 1.4 [1].

4. INFLUENCE OF THE COMPOSITION OF THE FURNACE DUST AND GAS ATMOSPHERE ON THERMAL LOADS ON WALLS AND HEAT LOSSES WITH EXHAUST GASES AND COOLING

The calculation of the fluxes of thermal radiation of the arcs on the water-cooled panels of the walls was carried out for the ASF-100 furnace for the period of the end of the melting of the charge, the arcs burn on a liquid metal bath (Figure 4).

The parameters of each of the three arcs are as follows: power 18 MW; voltage 260 V; current 69.2 kA; length 300 mm; $\alpha_{ad} = 0.92$. The calculation of the heat fluxes of the radiation of the arcs was carried out on the sections of the walls located opposite the electrodes and between the electrodes at a depth of arc penetration in the furnaces and a metal bath of 70 mm and 300 mm in the radiant, $k = 0$, and absorbing, $k = 0.7$, furnace atmosphere. In fig. 5 shows the results of calculating the flux densities of thermal radiation of arcs on sections of the walls located opposite the arcs (a) and between the arcs (b) in the radiant (I) and absorbing (II) atmosphere of the furnace.

In the absence of purging the bath with oxygen and supplying coal powder to the injectors, the furnace atmosphere approaches radiant with $k = 0$–0.1, and the heat fluxes of radiation from arcs to the walls reach maximum values of 600 kW/m$^2$ at a height of 0.5 m from the level of the metal bath, heat fluxes of radiation of arcs decrease along the height of the walls to 260 kW/m$^2$ at a level of 2 m from the bath. Similar values of the heat flux densities on the water-cooled wall panels were obtained as a result of experimental measurements: the heat flux density on the water-cooled wall panels varies from 100–300 kW/m$^2$ in quasi-stationary modes to 600–1000 kW/m$^2$ in dynamic processes [12].

When the metal bath is purged with oxygen and coal powder is injected into the bath by injectors, the absorption coefficient of the furnace atmosphere increases to $k=0.7$, the heat fluxes of arc radiation on the walls decrease by 3-8 times and amount to 150 kW/m$^2$ at a height of 0.5 m.
from the level of the metal bath and 30 kW/m$^2$ at a level of 2m from the bath. Consequently, in the absence of purging the metal bath with oxygen and with the coal powder injector not working, the thermal loads on the walls reach their maximum values and this period of operation is the most difficult for water-cooled wall panels. In the radiant atmosphere of the furnace, the heat losses with cooling water of the panels reach the maximum values, and the heat losses with gases reach the minimum values (Fig. 5). The results of calculations and the above conclusion confirm the results of experimental studies of the operation of the ASF-10 and ASF-100 furnaces with a water-cooling arch [13]. The heat loss with water of water-cooled panels depends on the melting period and, accordingly, the smoke content of the furnace atmosphere. The smoke content of the furnace atmosphere is maximal during the melting period, decreases during the oxidation period, and continues to decrease during the reduction period. At the maximum smoke content of the furnace atmosphere, most of the thermal radiation of the arcs is absorbed by the gases and a smaller part of the radiation reaches the wall panels and is absorbed by the cooling water. At the maximum smoke content of the furnace atmosphere, heat losses with water are minimal.
Figure 5. Distribution of the flux densities of thermal radiation of arcs, 300 mm high, along the height of the walls of the ASF-100 furnace at a depth of 70 mm arcs in the transparent atmosphere of the furnace (I), in the absorbing atmosphere of the furnace (II) along the sections of the walls located opposite the arc (a) and between arcs (b).

With minimal smoke and a radiant furnace atmosphere, most of the thermal radiation from the arcs reaches the water-cooled wall panels and is absorbed by the water. Heat losses with water are maximal with minimal smoke content in the atmosphere. Thus, depending on the absorption coefficient of the dust-gas atmosphere of the furnace, the heat losses of the arc radiation carried away by the exhaust gases and water of the water-cooled panels are redistributed. The calculation results are confirmed by the results of experimental studies: during the melting of the charge, when the absorption coefficient of the furnace atmosphere has a maximum value, the losses with cooling water amount to 10% of all losses with cooling water for melting, during the oxidation period this indicator is 35%, during the reduction period, when the furnace atmosphere is close to radiant, heat losses with cooling water of the panels is 55% of the heat losses with cooling water for melting [13]. Thus, the results of experimental studies of heat fluxes incident on water-cooled panels and heat losses with cooling water confirm the results of calculations of heat fluxes of arc radiation onto walls in ASF-100 furnace in a radiant and absorbing furnace atmosphere.

The wall sections located between the electrodes are located at a large distance from the arcs compared to the wall sections located opposite the arcs, so the heat fluxes of arc radiation on these wall sections are less than on the sections located opposite the electrodes and arcs. Figure 5, b shows the distribution of the heat radiation fluxes of the arcs on the sections of the walls located between the arcs. As can be seen from the calculation results, Fig.5, b, the heat fluxes of arc radiation at a wall height of 0.5m are 360 kW/m² in a radiant medium, which is 1.7 times less than the fluxes to the wall sections located at a similar height opposite the arcs. At a height of 2 m, the heat fluxes of arc radiation in a ray-transparent medium to the wall sections located between the electrodes are 200 kW/m² or 1.3 times less than the heat fluxes of arcs to the wall sections located opposite the electrodes and arcs. The fluxes of thermal radiation of arcs in the absorbing medium to the wall sections located between the electrodes are 1.3-1.7 times less than the heat fluxes of arcs to the wall sections opposite the electrodes.

5. CONCLUSION

The conducted analytical studies have established the following. In the chipboard from the conveyor loading of the charge, the arcs burn all the time on the metal bath, therefore, during the melting process, they tend to maintain the foamed slag to close the arcs, screen their thermal radiation on the walls and roof and increase the thermal radiation on the metal bath, slag. For foaming the slag during the entire melting time, coal powder supplied to the slag by an injector is used. The operation of the injector is characterized by an increase in the amount and coefficient of absorption of gases removed from the furnace. Losses with exhaust gases are maximum and amount to 31% in the consumable part of the ASF energy balances with conveyor loading of the charge. The dust-gas atmosphere in the ASF with conveyor loading has the maximum absorption coefficient, the thermal radiation of the arcs is absorbed by the dust-gas atmosphere and the heat fluxes onto the water-cooled panels have a minimum value, the losses with cooling water are minimal.

In furnaces with loading the charge with baskets, the arcs burn for a long time in wells, shielded by the charge, as a result of which the consumption of coal powder is 1.5 times less compared to ASF with conveyor loading of the charge, heat losses with exhaust gases are less and amount to 22%, losses with cooling water 8%. In ASF, heat fluxes from arcs to walls reach maximum values in a radiant medium, decrease with an increase in the dust content of the atmosphere and reach minimum values at the maximum absorption coefficient of the dust-gas atmosphere of the furnace.

NOMENCLATURE

q-density of heat radiation flux
Ppower, kW

k-absorption coefficient of gas medium

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