Conference Paper

Mathematical Model of Heat Exchange of a Plasma Furnace

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Abstract

The principle of operation of the periodic action plasma furnace and options for describing the heat-and-chemical processes occurring in such furnaces are considered. There are given equations of heat transfer by radiation and convection, features of the thermal interaction of plasma with the solid particles surface, the influence of thermophysical properties and composition of particles on the efficiency of the furnace operation, as well as the possible chemistry of reactions to the parameters of plasma heating.

Keywords: plasma furnaces, thermophysical processes, radiation, convection, plasma heating chemistry

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1. Introduction

Plasma furnaces have become increasingly widespread in industry in recent years. However, the scientific justification and description of the thermophysical processes taking place in such furnaces has been developed relatively weakly. This circumstance complicates the establishment of rational thermal regimes of these furnaces, as well as their optimal design parameters. That development of scientific basis of design and operation of thermal plasma furnaces is the main content of the work.

Consider the operation of a plasma furnace for remelting chemical and automotive catalysts.

2. Technology of Plasma Melting Process

The spent chemical catalysts are removed from the carrier containers and brought to a grain size of about 1 mm, suitable for feeding into the plasma furnace. Also suitable material are waste catalytic converters taken from vehicles with an exhausted life,

which are decanted to separate the monolithic ceramic 'mesh' from the stainless steel shell. The surface of the ceramic monolith is coated with a thin layer containing the catalyst (i.e., noble metals). The stainless steel shell is removed and sent for recycling, and the ceramic monolith is crushed into particles of 2 to 8 mm in size.

The crushed catalyst was mixed with a flux (CaO for automotive catalysts, CaO + SiO_2 – for chemical catalysts), magnetite (hematite, Fe_3O_4, to provide iron in a metal-collector), and a reducing agent (metallurgical coke, C). The resulting mixture is stirred for 15 to 30 minutes for homogenization, after which it is ready for loading into a plasma furnace.

After the plasma oven has warmed up (according to the heating schedule about 6 hours) and reached stable mode, the initial mixture of materials is fed through the holes in the roof of the furnace using auger conveyors operating at a given speed. The feed rate is controlled by weight loss in the feeder. Melting and vaporization of volatile provides by plasma arc burning at the tip of the water-cooled cathode 50 mm. The flux-forming additives guarantee complete melting of the inorganic component in the charge at the operating temperature of the furnace (usually from 1400 to 1800°C), because the eutectic melting point of the whole composition is provided, and the flux additives also reduce the melt viscosity, ensuring maximum mixing of reagents and a reducing agent in the furnace hearth.

Coke reduces the iron oxide to the metal in the form of droplets, and the bubbles of the resulting carbon monoxide exit through the slag phase, ensuring good mixing of the melt. Iron drops serve as a medium for the dissolution of platinum group metals (hereinafter – PGM). The denser iron-collector and PGMs fall to the bottom of the furnace, and the less dense slag floats on the surface, from where it is continuously removed through the slag tap.

The furnace has a graphite crucible, which holds well the iron-collector and slag; the roof and the upper sections of the furnace are cooled by water and lined with high-quality cast alumina (corundum) refractories, which provide effective thermal insulation. The slag is removed from the furnace in a continuous mode through a submerged channel with a slope to the casting trough. As a sufficient volume of metallic melt accumulates in the graphite crucible, metal is periodically produced. The path of the plasma current circuit passes through two graphite electrodes located in the base of the furnace. Additional openings are provided for the camera, material loading, exhaust air duct, purge gas, temperature and pressure sensors, etc.

The cathode plasmatron is inserted into the furnace roof through a spherical stuffing box. Moving the burner vertically and rotating in a horizontal plane adjusts the robot

manipulator, which provides an efficient distribution of heating across the furnace. Plasma current and, accordingly, input power, are regulated by the SCADA system to maintain a stable state of the process. The temperature of the drainage slag is continuously monitored by an optical pyrometer.

Drainage slag from the furnace gets directly into the bowl-catcher, where it solidifies into the vitreous blocks. Alternatively, a water-cooled slag conveyor is used instead of the bowl catchers. The metal melt and bottom slag are poured into a heated ladle with refractory lining. The remaining excess slag is poured through the casting ladle sock and collected into a steel slag bowl. The molten metal and slag from the ladle are poured onto the landfill (pouring table), where they spread into a thin (about 10 mm) sheet, and rapid cooling is achieved. When solidified, the melt cracks into smaller fragments. The metallic melt in its properties and composition is very close to white iron, contains approximately 1–6 wt. % of carbon, which ensures the fragility of the material and lowers its melting point. The content of silicon and phosphorus in the metallic melt depends on the quality of the raw materials and the quality of melting. PGM content in the molten metal is unknown, because it is a trade secret.

The gases leaving the furnace consist mainly of argon (from the plasma torch and purge) and carbon monoxide (from the reduction reactions), it is also possible the presence of some quantities of steam (from moisture in the feed). The off-gases also capture a small amount of solid particles. Effective management of an exhaust fan to maintain the desired suction pressure inside the furnace minimizes the transfer of solid particles from the furnace, but it should be noted that an excessive comminution of the charge material to obtain a fine fraction only aggravates the problem, which will inevitably have to decide during operation of the system.

The gases leaving the plasma furnace enter the oxidizing furnace (secondary combustion chamber), with a minimum operating temperature of 850°C, while the residence time of the gas phase from the time of introduction of the oxidant is at least 2 seconds. To heat the oxidizing furnace to the desired temperature, an adjustable burner is used. In addition, the blower provides fresh air for combustion in the base of the oxidizing furnace, and the return air for complete combustion and cooling can be introduced independently at the outlet of the oxidizing furnace. Most of the ash and fine particles resulting from the incomplete combustion cycle and leaving the furnace is collected in the bunker of the oxidizer furnace.

The oxidizer furnace is connected to the filtration unit by an air duct, in which there is a rod-cleaning hole and apertures for introducing compressed air, through which short and powerful air injections are delivered to carry the dust to the filtration unit. In the

next stage of purification of waste gases, solid particles are filtered on highly efficient two-stage ceramic filtration units. The first stage of filtration of particles coming from the furnace serves to increase the efficiency of PGM extraction, the filtered particles return to the plasma furnace. The second stage of filtering consists in dry gas scrubbing by introducing sorbents, such as hydrated lime, to capture and neutralize SO_2.

Further, the afterburning and purification from the solid particles, the exhaust gases are sent to the exhaust fan (smoke exhaust) and discharged to the atmosphere through the chimney. The whole process is controlled by an exhaust fan, which creates a low vacuum in the furnace. This ensures that the process gas is retained in the ducts without leakage to the outside. The exhaust fan has a speed adjustment to maintain pressure in the main plasma furnace. Finally, the filtered and purified off-gases are discharged to the atmosphere through a vertical chimney.

This technology is similar to electric arc furnaces, but it has the following advantages:

1. plasma heating is a 'clean technology', there is no contamination of the melt by products of combustion/interaction of graphite electrodes;
2. much less burnt part of the melt (metal) part;
3. good sealing of the furnace allows creating a protective controlled atmosphere (due to the plasma-forming gas), which leads to low oxidation of the smelting products;
4. more uniform and volumetric distribution of heat in the furnace zone;
5. the plasma furnace does not require (as opposed to an electric arc furnace) constant and continuous regulation of the arc length, because there is a certain constant arc length that depends on the current strength and at which the optimal and efficient heat transfer to the melt bath is carried out;
6. lower power consumption with the same melting parameters (mass of processed raw materials, processing time, working volume of the furnace);
7. higher heat output with smaller dimensions.

3. Thermal Processes in Plasma Heating

When exposed to the plasma arc on the surface of processed material different physico-chemical processes flow. The nature of their flow is determined by the

temperature, speed and heating time, the cooling rate of the plasma torch, the properties of the material being processed, and so on. The plasma heat treatment of solid materials is based on the ability of a plasma arc to create, on a small portion of the surface, high heat flux densities sufficient for heating, melting, or vaporizing virtually any metal. The main physical characteristic of the plasma effect is the temperature field, the value of which makes it possible to estimate the temperature at different points of the thermal action zone (at different times), the heating and cooling rate, and ultimately the structural state and phase composition of the surface layer of the material.

Thermal processes during plasma heating require the use of a concentrated heating source with a heat flux density on the surface of the material from 10^3 to 10^6 W/cm^2. The main factor that distinguishes plasma heating from laser heating is the mechanism of interaction of the energy source with the material. With laser heating, the light flux of radiation directed toward the surface of the material is partially reflected from it, and partly passes into the depth of the material. Radiation penetrating into the depth of the material is almost completely absorbed by free conduction electrons in the surface layer of 0.1 to 1 microns thick [1, 11–13]. Absorption leads to an increase in the energy of the electrons, and as a result, to the intensification of their collisions between themselves and the transfer of energy to the crystal lattice of the metal. The thermal state of the metal is characterized by two temperatures: the electron temperature Te and the lattice state Ti, and T_e»T_i. With the passage of time (beginning with the relaxation time $t_P \sim 10^{-9}$ s), the temperature difference ($T_e - T_i$) becomes minimal and the thermal state of the material can be characterized by a common temperature – T_m. Further distribution of energy into the material is carried out by thermal conductivity. Heating of the surface of the material by a plasma arc is provided by forced convective and radiant heat transfer:

$$q = q_k + q_l. \tag{1}$$

For approximate calculations of heat fluxes in the surface, a model of radiative and convective heat transfer is used, based on the theory of the boundary layer [1]. The density of the convective heat flux is determined from the expression:

$$q_K = \sum \lambda \frac{\partial T}{\partial y} + \sum \rho v H + \rho \sum K_m v. \tag{2}$$

In the general form, convective surface heating is caused by the transfer of the energy of the plasma arc under the action of heat conduction, diffusion. In practice, a simpler expression is used:

$$q_K = \alpha \left(T_{plasma} - T_{surface} \right), \tag{3}$$

where α – is the coefficient of heat transfer,

T_{plasma} – temperature of the plasma arc on the outer boundary layer,

$T_{surface}$ – surface temperature.

The relationship between α and the parameters of the plasma arc is expressed in terms of generalized dependences (Nusselt number, Prandl, Reynolds, etc.); the choice for various cases of interaction of the plasma with the surface is given in [2, 3]. The fraction of radiant energy transfer from the plasma arc to the metal surface is from 2 to 8% of the total energy balance [3]. In the case of pulsed plasma arc proportion of radiant heat transfer increases to 20 ÷ 30%. The radiant flux to the unit area of the surface in the normal direction is determined as follows:

$$q_l = \xi_1 \xi_2 \cdot \sigma_c T^4, \tag{4}$$

where ξ_1 – is the integral absorptivity of the surface,

ξ_2 – blackness of plasma,

σ_c – the Stefan–Boltzmann constant,

T – plasma temperature [4, 14–16].

Taking into account that the heat exchange between the arc and the surface is mainly determined by the convective component of the heat flux, and neglecting the radiant heat exchange (with the exception of the pulsed plasma arc), we can calculate the heat flux from the expression of Fei–Riddel [5]:

$$q = 0,763 Pr^{-0,6} \sqrt{\mu\rho \left(\frac{\partial u_r}{\partial r}\right)_0} \left(\frac{\rho_0 \mu_0}{\rho \mu}\right)^{0,1} \left[1 + (L_e^n - 1)\frac{\alpha \Delta h_p}{h}\right](h - c_p^0 T_n), \tag{5}$$

or

$$q = 0,76 Pr^{-0,6} (\rho\mu)_\omega^{0,1} (\rho\mu)_s^{0,4} \left[1 + \left(L_e^{0,52} - 1\right)\right] \frac{h_d}{h_s} \sqrt{\frac{dv_e}{dr}} \left(h_s - h_\omega\right), \tag{6}$$

where Pr is the average Prandtl number,

$(\rho\mu)_\omega$ – is the density and the coefficient of dynamic viscosity of the plasma at the surface temperature of the body,

$(\rho\mu)_s$ – is the density and the coefficient of dynamic viscosity of the plasma at the temperature of the outer boundary of the boundary layer,

L_e – is the number of Lgos–Semenov,

dv_c/d_r – is velocity gradient at the critical point, equal to $\sim \mathbf{U}_{plasma}/d_{nozzle}$, h_s – is the total enthalpy of the plasma arc.

When the metal surface is heated by a plasma arc, the heating efficiency increases due to the electron current q_e:

$$q = q_k + q_l + q_e. \tag{7}$$

The additional thermal power due to the electron current is calculated from the expression:

$$q_e = I\left(v_0 + \omega \cdot \frac{5R}{2e}T\right). \tag{8}$$

The effective coefficient of efficiency of plasma-arc heating can reach 70 ÷ 85% [3, 6]. The energy balance of plasma heating at atmospheric pressure is as follows: 70% – convective heat transfer; 20% – electronic current; 10% – radiant heat transfer. When using a plasma arc as a source of thermal energy, the distribution of the heat flux along the heating spot is of the greatest interest. The distribution of the specific heat flux q_z in the heating spot is approximately described by the law of the normal Gaussian distribution [7–10]:

$$q_z = q_{2m}\exp(-Kr^2), \tag{9}$$

where K – is the concentration coefficient characterizing the shape of the normal distribution curve, and, consequently, the energy concentration in the heating spot,

q_{2m} – maximum heat flux.

The concentration coefficient plays a big role in plasma hardening processes, since regulates the heating rate of the surface layer of the metal. The maximum density of the heat flux at the center of the heating spot is related to the concentration factor: [7]

$$q = q_{2m} \cdot \pi/K. \tag{10}$$

The heat exchange between the plasma arc and the hardened surface occurs in the region of the heating spot, whose nominal diameter is:

$$d_\pi = \frac{3,46}{\sqrt{K}}. \tag{11}$$

At the border of spot heating heat flux is 0.05% of the maximum q_2 [6]. Parameters of the plasma torch operating mode exert a strong influence on the concentration coefficient. With increasing current intensity, K increases. A decrease in the diameter of the nozzle ($d_C \leq 5$) increases K. As the flow of the plasma-forming gas increases, the concentration coefficient has a maximum (Figure 1).

The concentration coefficient is greatly influenced by the method of gas supply, the geometry of the nozzle and the electrode. When using a nozzle with a focusing gas,

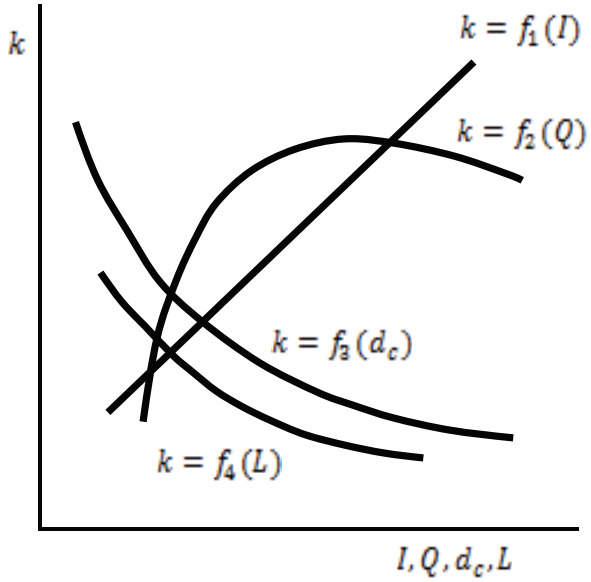

Figure 1: Change in the parameters of interaction of plasma with the surface of a solid body.

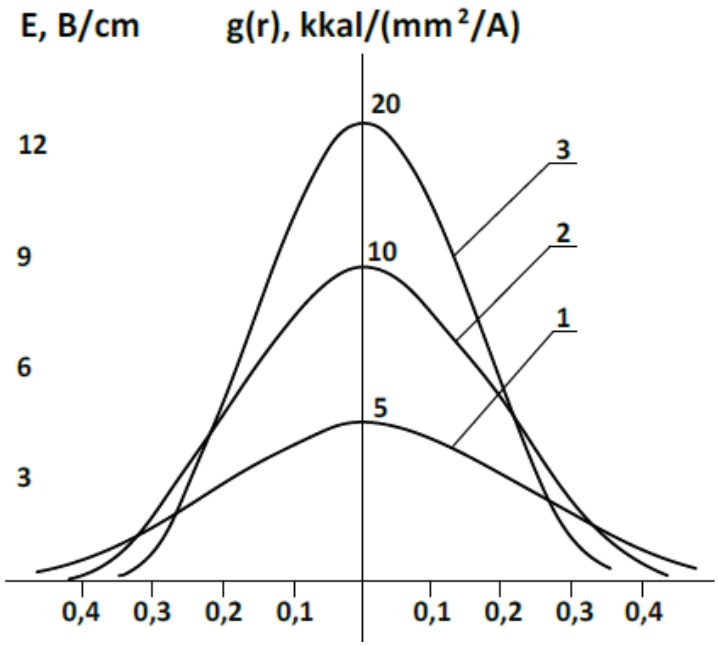

Figure 2: Distribution of the heat flux of the arc q (r) along the radius of the heating spot of a small amperage arc, depending on the compression ratio [6]: 1 – free-burning electric arc; 2 – slightly compressed electric arc; 3 – compressed electric arc.

the concentration coefficient increases. The energy characteristics of plasmatrons (arc voltage, effective thermal power, heat flux concentration, etc.) depend on the degree of reduction of the column of the arc, [3–6, 17–19]. Thus, the compression of an arc burning in argon at a current of 150–200 A (due to a change in the diameter of the

nozzle and its position along the length of the tungsten cathode) led to an increase in arc voltage and electric field strength in the arc column (Figure 2) [20].

4. Summary

Only the basic thermo-physical regularities of the interaction of plasma with the material being processed are considered. Issues of development of chemical reactions, the removal of harmful components of solids, loading of raw materials into the furnace and remove the finished product require special consideration. Especially important are problems associated with the technical and economic performance and constructing the most efficient furnaces workspace. So far, questions of numerical modeling of processes in plasma furnaces for various purposes have not been developed at all. All this requires intensification of scientific research in this field.

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