Investigation of electrophysical properties of smelting products and their connection with engineering process

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Abstract
Methods for control of decarburization of steelmaking vessel pool are analyzed. The possibility of automatic monitor and control of decarburization rate of metal is investigated. Information concerning decarburization process of converter pool is studied.
Key words: CONVERTER, RATE, SYSTEM, PROCESS, METHOD, PARAMETER, CARBON, RESULT, TEMPERATURE, POOL, THERMODYNAMICS, EXPERIMENT, GAS.

Introduction

Pool of basic-oxygen convertor, as multi-loop controlled object, is three-phase, multicomponent thermodynamic system, where on the background of turbulent transport there take place interrelated heat and mass exchange, hydrodynamic, chemical and other irreversible processes. State of the art of measuring equipment does not allow to fulfill direct control of propagation velocity of physical and chemical processes in aggressive high temperature fluid. These processes determine controlled coordinate of the object - temperature and carbon content in the metal [1].

There are a lot of control methods for pool parameters. These methods are based on the laws of thermodynamics [2], kinetics [3] and usage of statistical dependences [4]. As a rule, known methods are rather complicated, they are characterized by the absence of back-coupling from the process, lead to satisfactory results only in narrow range of change of starting and ending process parameters. These means often allow to control only one outcome parameter – content of carbon in the pool [5] or its temperature [6].

In such a way, usage of such known methods lead to failures as a result of measuring and as a consequence to nonoptimal control of converter operation.

Key elements of automatic process control system (APCS) are forecasting filters, which allow to get information about controlled parameters of the process without direct change of the last. Main requirements to the forecasting filters are reliability, absence of random walk, simplicity of operation. Information carriers about scavenging outward - parameters of waste gas, are best explored among indirect determination.

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Problem statement

The aim of researches is continuous information uptake about the course of convertor operation under eloctrophysical parameters of melting products.

Research results

Most of the processes of mass and heat transfer in the convertor is followed by the complex of electric phenomena arising on the phase interface. During heating surface contact, there observed between them charge exchange, which leads to the loss of neutrality of contacting bodies. As ion charge is relatively large and electric capacity on the phase interface is small, then during transfer even small amount of ions to the boundary surface, there may arise rather significant electric potential. Herewith in surface layers of each phase there concentrated eclectic charges, which are equal in value, but opposite in sign.

Because of delayed burning in atmospheric oxygen of products of incomplete oxidation of carbon pool, above the vessel mouth there forms flame bush. Researches [7] fulfilled on 1.5 ton laboratory converter and 55 ton industrial converter, determined that convertor flame in space has different electrical conductivity both in depth and height. Main volume of flame has rather big (hundreds of kilohms) electrical resistance. Herewith during probing device introduction into core flame at the depth 1.3…1.5 m there was found high-conductivity area, resistance to which varies within dozens of Ohms, which speaks for the presence of nonuniform gas ionization in zone of CO combustion, as combustion procedure is followed by formation of great amount of free electrons. Behavior of electrical conductivity of the flame core qualitative coincides with the change of velocity of pool decarburization.

At Karagandinskij metallurgical plant there were probed detectors of current potential of gas phase with long-run serviceability in conditions of high temperatures and increased dust content [8]. Test of detectors on heavy-duty convertor showed that the presence of stochastic connection of change of carbon weight ratio in metal within the limit of 0.1…2.0 % with the variation value of potential of gas phase (index of correlation r = 0.86). Behavior of rate change of decarburization, determined on the base of gas analysis data, repeated tendency of change of potential curve of waste gas.

Physical parameters of the flame we investigated on 160 ton convertor with the help of double water-cooling probing device placed in the upper part of caisson. Structurally sensitive element of detector is fulfilled in the form of two parallel cylindrical electrodes, which entered into flame core. Linear density of flame electrical conductivity χ, Sm/m, was found from the expression:

$$\chi = [R(d + \pi l/\mathrm{arch}D/d)]^{-1}, \qquad (1)$$

where R – electrical resistance of interelectrode interval, Ohm; d = 0.05; l = 0.8; D = 0.15 – diameter and length of electrodes respectively, distance between the last, m.

By statistical treatment of data of experimental massive there obtained dependence of velocity pool decarburization on the linear density of flame electrical conductivity

$$v_c = \alpha_1 + \alpha_2 \ln[\alpha_3(\chi - \alpha_4)] \qquad (2)$$

(correlation ratio η=0.59, root-mean-square deviation σ=0,009 %/min, accuracy of correlation factor P>0.950),

where v_c – rate of convertor pool decarburization, %/min; α_i – coefficients for considered object equal α_1 = 0.612 %/min, α_2 = 0.063 %/min, α_3 = 1 m/Sm, α_4 = 0.214 Sm/m.

To obtain more accurate results we developed method, which is based on the measurement of surface density of current intensity. Test was fulfilled on the convertor, working in the regime without reburning of waste gas. In gas pipe there were fitted two pairs of electrodes, one of which they joined with electric current meter and the other one with gas mhometer. Electromagnet was placed below the electrodes.

During motion of ionized gas in magnet space there arise electromotive force (EF), which causes current strength in work body

$i = \chi(wB - E)$, (3)

where i - aerial density of current strength flowing in the gas, A/m^2; w – gas velocity m/s; B – areal density of magnetic flow, T; E – linear density of strain of external electric field, which depends on the sonde design and electric resistance of loading, V/m.

For electrodes in the form of flat plates

$E = iR_l F/D$, (4)

where R_l – load resistance, Ohm, F – area of electrode surface, m^2.

For converter without reburning, velocity of pool decarburization is connected with gas rate by the expression

$v_c = 0{,}0536wF_r/m(1 - b\tau)$, (5)

where F_r – area of surface of cross section of gas pipe m^2; m – metal mass, t; b – coefficient of iron loss, determined by technological peculiarities of the process, min^{-1}; τ – running time of blowing, min.

Dependence (5) is true also for convertor with reburning of waste gas during calculations in flame core. Solving the equations (3)... (5) we will obtain

$v_c = 0{,}0536iF(1 + \chi R_l F/D)/\chi Bm(1 - b\tau)$ (6)

Realization of dependency (6) allowed to control the rate of convertor pool decarburization with the accuracy not lower than 0.01% min. Because of complexity of described methodology, connected with creation of powerful magnetic field in gas pipe, we developed simpler in equipment design way based on the measuring of gas parameters in two points along the flow. In this case gas rate is determined by the expression

$w = L/\Delta\tau$, (7)

where L – distance between control points, m; $\Delta\tau$ – time of duration of gas passage of the distance L, min.

Measuring electrode for realization of method is fulfilled in the form of cylinder, which has longitudinal-through, blown by air or neutral gas channel, which is used as optical one for outcoupling of gas within sight of noncontact pyrometer.

Analysis of gasdynamic exhaust gas stream shows that the flame core – is the most meaningful area of parametering. As the flow of exit gas is turbulent (Reynolds criterion Re $\approx 10^5$), there exists in it fluctuation of physical characteristics with frequency 50…80 Hz. So typical scale of inhomogenuity at mean flow velocities w= 10…20 m/s is $\Delta l = w/f$ = 0.2…0.3 m.

Sequence recordation of moving inhomogenuity of electrical conductivity in two flow points, located at the distance L, allows to determine the velocity of gas in the core, $w_c = L/\Delta\tau$, where time duration $\Delta\tau$ is found from the condition of maximum of cross-correlation function $\max(1/\tau_*)\int_{(\tau)} \chi_1(\tau)\chi_2(\tau - \Delta\tau)d\tau$; τ_* – averaging time, min; χ_1, χ_2 – linear density of flame conductivity between electrodes in corresponding points of control Sm/m. As the experiment showed, reliable determination of the value $\Delta\tau$ by correlation way is possible at $L = (2…3)\Delta l$ = 0.4…0.9 m.

For control of metal temperature in converter, there was investigated a method, which is based on the calculation in interelectrode interval sonde-land of electrical conductivity of the flame according to the value of applied electric tension and current. Ohm's law for plasma is true only at small tensions between electrodes at initial (rectilinear) area of current-voltage characteristic. At tensions, which are bigger than critical ones, current strength through the plasma does not depend on the value of applied tension, i.e. comes for “enrichment” up to tension, wherein there occurs breakdown in gas and the discharging lights up.

We considered metallic pool as emitter. Intensity of current force of thermoelectron emission from the surface of smelted metal-cathode in working space of convertor, which is connected with metal temperature and electronic work function, is investigated. Current measurement of electric conductivity in regime of enrichment between electrode and metal at equal positive and negative tension in the electrode allows to determine thermal emission current strength from metal surface, and control of contact electric potential between electrode and metal allows to find electronic work function from metal surface during blowing.

Gas above the emitter changes thermionic current. Current in the convertor flame is conditioned by ions and electrons. Due to low mobility of ions as compared with electrons, current force in regime of enrichment is limited by ionic component of plasma.

Difference of current strength values of enrichment at negative and positive tension on the electrode towards the pool is conditioned by difference of surface area of electrode and pool and contribution of thermionic current strength in regime of enrichment at positive tension on the electrode.

At negative towards the pool tension on the electrode, placed in core flame, current strength of enrichment is equal to

$$J_{e1} = 2F_e i_U , \qquad (8)$$

where J_{e1} - intensity of current of enrichment at negative tension on the electrode, A; F_e – emissive surface area of electrode, determined by geometry, m^2; i_U – aerial density of ionic current force from plasma, A/m^2.

At positive tension on the electrode there occur bubble ionic current force on the increase of thermal emission from the metal surface

$$J_{e2} = 2[(F_{\text{м}} + F_c)i_U + F_{\text{м}} i_t], \qquad (9)$$

where J_{e2} - intensity of current of enrichment at positive tension of the electrode, A; $F_{\text{м}}$ – emissive surface area of metal (determined by geometry of pool), m^2; F_c – surface area of cool (non- emissive) area, which electrically contacts with emissive surface area of metal (determined by convertor construction and location of electrode), m^2; i_t – areal density of thermionic current force of enrichment, A/m^2.

Areal density of thermionic current force of enrichment is determined by metal temperature and work function of emitter with the help of Richardson-Deshman expression

$$I_t = \alpha_0 T^2 \exp[-A/(kT)], \qquad (10)$$

where $\alpha_0 = 120.4 \cdot 10^4$ – multifunctional thermoelectric Richardson constant for metals, $A/(м^2 \cdot K^2)$; T –metal temperature, K; $A = e\psi$ - electronic work function of a metal, count off from Fermi edge, J; $e = 1.6 \cdot 10^{-19}$ – absolute value of electron electric charge, Kl; ψ – current potential of releasing of electrons from metal surface, V; $k = 1.38 \cdot 10^{-23}$ – Boltzmann's constant J/K.

According Schottky effect external electric field reduces emitting work. As smelt surface is the mixture of metal and slag, than the value ψ for such surface is within the limits 3.8…5.3 V, which gives for representative temperature the value of thermionic current strength ≈ 10^{-2} A. Change of ψ due to chemistry variations of smelt surface during blowing is controlled with the value of contact potential difference between electrode and pool according to Thomson-Zisman process

$$\psi = U_{\text{к}} + \psi_e, \qquad (11)$$

where $U_{\text{к}}$ – contact potential difference, determined according to the shift of current-voltage characteristic at minimal value of current strength of conductivity, V, ψ_e – tension of releasing of electrons from electrode surface, V.

Taking into account formulas (8)…(11) we will obtain an expression for calculation of metal temperature:

$$\alpha_0 T^2 \exp[-108 \cdot 10^4 (U_{\text{к}} + \psi_e)/T] = \alpha_1 J_{\text{м}2} - \alpha_2 J_{\text{м}1}, \qquad (12)$$

where $\alpha_1 = 1/(2F_{\text{м}})$ and $\alpha_2 = 1/(2F_{\text{м}}) - F_c/(2F_{\text{м}}F_e)$, m^{-2}.

From the expression (12) it follows that

$$\ln(\alpha_1 J_{\text{м}2} - \alpha_2 J_{\text{м}1})T = -1.08 \cdot 10^{-4}(U_{\text{к}} + \psi_e) + 2T\ln(\alpha_0^{0.5} T). \qquad (13)$$

In the figure 1 there given an example of iterative calculations according to formula (13) of converter pool temperature T = 1800 K at the following values of parameters: $U_{\text{к}}$ = 0.8 V, $J_{\text{м}1}$=1.064 A, $J_{\text{м}2}$ = 2.721 A, ψ_e = 4.1 V, α_1 = =3.8 $\cdot$ 10^{-2} m^{-2}, α_2 = 0.167 m^2. Numerical values of sequence of four-crane successive approximation are, K: 1600.00–1813.52–1799.15–1800.05. Further calculations are inappropriate, as sought-for value is within the latest calculated values, which differ less than on 1 K.

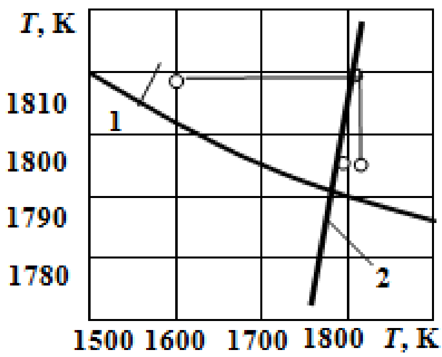

Figure 1. Graphical interpretation of iterative solution of equation (13) towards T: 1, 2 graphs, corresponding to left and right parts of (13)

Let us estimate error of method due to emitter temperature influence on the work of electronic work function. Let us assume temperature dependence of electrical potential of electron releasing as the expression

$$\psi(T) = \psi(T_*) + \alpha(T - T_*), \qquad (14)$$

where T_* –is base metal temperature, K; $\alpha = d\psi/dT$ – temperature coefficient of electron releasing potential, which equals 10^{-5}V/K.

Theoretical error of metal temperature control within change of the last ± 50 K (encloses almost all range of smelted steel grades) is 0.2 K. For all range of change of pool temperature along the blowing, the error does not exceed 1K.

Industrial tests of the method is fulfilled at Yenakiieve iron and steel works. Installation contained metric water cooled electrode, sensing element of which was fixed in the flame core. To fulfill reliable contact with the smelt, metallic electrode, which is energetically decoupled from steel structures, was placed into convertor lining. Measuring and contact electrodes are elctricaly connected through external circuit and plasma, forming complected circuit measuring electrode – flame plasma- pool – contact electrode - conversion device - measuring electrode. Current strength in this chain in forward and backward directions differs on the current strength of thermal emission from the pool surface, experimentally conforming bubble of current strength of enrichment. In the conversion device there measured volt-ampere characteristic per time less than fluctuation time in plasma. Negative leg of volt-ampere characteristic gives the value J_{e1}, positive – J_{e2}. According to the shift of volt-ampere characteristic towards the beginning of coordinates one may determine the value $U_к$, according to current potential of measuring electrode releasing ψ_e, one may determine the value ψ.

Industrial tests on the method showed that mean-square deviation of required parameter is 12.3 K. Fulfilled researches are in line with the work [9] concerning creation of temperature sensor of emitter within the limits of control 1700 K.

Together with electrophysical properties, we studied opticospectral properties of the flame below the vessel mouth. Spectrum was taken with the help of prism spectrogram with quartz optics ISP-30 with the distance 30 m.

During blowing flame spectrum has continuous background, where separate lines are almost indistinguishable and flame emission is little different from emission of black radiator. It is stated that continuous background is created with dust particles, portion of which in the flame till the end of blowing reduces rapidly.

Till the moment on blowing end from the converter mouth there arises flame, which has well-defined line spectrum, which in its turn is connected with chemical composition of pig iron, blowing technology and weight ration of carbon in the pool. So for conditions of Yenakiieve iron and steel works (open-hearth pig iron was processed, blowing was fulfilled trough four-jet tuyere with nozzle inclination to the vertical 13^o, at oxygen consumption 450 m^3/min) there typical the lines in the blue light with wave length 4520, 4550, 4700, 4800 $\overset{0}{A}$, which start disappearing at carbon rate equal 0.5% and disappear at 0.25%. Linear flame spectrum at the moment of blowing end is probably conditioned by the absence of dust in it, which is the result of reaction zone disappearance. Fulfilled researches allowed to use characteristics of flame spectrum for automatic correction of metal analysis after turn-down. If there are blue lines of metal in spectrum, final blow is calculated according to oxygen volume.

According to existing at converter plants technology of pool blowing is fulfilled till value of carbon content not lower than in the specified steel grade, take metal sample for analysis and if necessary, fulfill final blow till required carbon content. Operations concerning sampling and metal analysis, which take 5-7 min., are not always justified, especially if carbon content is higher than specified one.

Fulfilled by many researches control of electric conductivity of tuyere chain – pool allows precisely determine the moments of intensive pool foaming, flooding of oxygen nozzle and sinking of the pool below the cross section of tuyere end. Besides, calculation of electric conductivity allows to fix tuyere before blowing at the specified distance from the surface of dead metal, which is very important for normal process, and without delay to determine smelting ignition point.

In the work [10] eclectic conductivity of convertor pool was measured in the chains electrode – electrode and tuyere – electrode. In the first case electrical contact was fulfilled through iron electrodes, located in the converter lining at various heights. Herein we were able to sample only the conductivity of surface layer of refractory material, which is determined by its temperature and chemical composition. One may suppose that this method will be more useful during study of physic-chemical processes occurring on the surface layer of lining, especially during heating. In the second case the second electrode was electrically isolated tuyere. Overseeing the conductivity of converter pool in the area tuyere-electrode allows to define moments of intensive foaming of metal-slag-gas emulsion and flooding of oxygen tuyere.

Main difficulties, which arise during change of conductivity of metallic pool, are connected with the necessity to provide electric isolation of the tuyere or special sonde-electrode from metallic construction of the plant. This circumstance considerably complicates control system, reduces reliability and accuracy of measurements, as it is rather complicated to keep electrical resistance of isolation at the required level in conditions of high dust content of convertor plant. Besides, conductivity signal is depraved by the influence of gas and chemical electromotive force (EMF) of convertor pool. That is why the possibility of industrial usage of electrical conductivity of tuyere-pool chain requires background study.

Conclusions

Fulfilled researches of electrophysical characteristics of smelting products show that these parameters are firmly connected with processes occoring in the pool and may be used as forecasting filters during building of mathematical model of object control.

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