Analysis of the technique for experimental determination of the efficient heat transfer coefficient during drying of iron ore pellets and charge in the dense layer

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The paper presents the experimental thermogravimetric unit for determination of the efficient heat transfer coefficient during drying and roasting of sintering charge from iron ore lump and pelletized raw material within the temperature ranges and aerodynamic conditions of the operating roasting conveyor machines, during complicated and power-intensive chemical-metallurgical process of iron ore raw material roasting in a moving dense layer with cross feed of the heat-transfer gas. The techniques for experimental determination of the efficient heat transfer coefficient during drying of iron ore pellets and charge in the dense layer are analyzed. It was scientifically substantiated that two periods should be underlined during drying of capillary-porous bodies (e.g. iron ore pellets); these are the periods of permanent and dropping drying rate. It was found out that moisture evaporation from the surface of a wet body during the first drying period occurs in the same way, as from free water surface, and according to the same laws. The temperature of a drying body does not increase practically, because transferred heat is consumed for evaporation until the whole free (capillary) moisture will evaporate. It was established that the second period starts from evaporation of bonded moisture, and drying rate is determined mainly by steam diffusion inside a wet body. Two independent methods were revealed on the base of analysis of the techniques for experimental determination of the efficient heat transfer coefficient. One of these methods is based on enthalpy variation of a drying agent, and another – on weight variation of a wet iron ore sample. It is noted that the experimental thermogravimetric unit, which was designed by the authors, allows to implement both of these methods. The error of variation of the efficient heat transfer coefficient is evaluated.

Key words: iron ore raw materials, thermogravimetric unit, drying, temperature, heat and mass exchange, roasting conveyor machine, heat-transfer gas, efficient heat transfer coefficient.
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Introduction

The technology of thermal method for metal manufacture includes multi-stage thermal effect on iron ore raw material, thereby efficiency of the most stages is determined by intensity of heat and mass exchange processes [1, 2]. Rational use of raw material resources and energy-saving measures causes necessity of studying the features of heat and mass transfer processes and ways of their intensification [3, 4].

Difficulties of experimental examination of all conditions of conduction of heat and mass exchange processes in iron ore raw materials during roasting determine the way of development of mathematical models and their use for identification and optimization [5, 6]. Such searching strategy for the most acceptable technical solutions requires knowledge about the properties of iron ore materials, heat carriers and parameters of heat and mass exchange themselves for determining description of chemical and metallurgical processes and technological equipment [7, 8]. The technique for examination of mass exchange iron ore drying processes in the dense layer is presented in this work in order to obtain the heat and mass exchange coefficients [9, 10]. The experimental thermogravimetric unit for determination of the efficient heat transfer coefficient during drying and roasting of iron ore pellets and sintering charge is developed [11, 12].

The aim of this research is examination of the efficient heat transfer coefficient during drying and roasting of iron ore pellets and sintering charge using the experimental thermogravimetric unit (which was developed by the authors) and conduction of natural experiments according to the suggested technique for determination of the heat and mass exchange coefficients in energy-intensive complicated chemical and metallurgical processes of drying and roasting of iron ore raw materials.

The research methods: experimental investigations and analysis of the techniques for experimental determination of the efficient heat transfer coefficient during drying and roasting of iron ore pellets and sintering charge in the dense layer, in order to calculate thermal and aerodynamic procedure for roasting of iron ore raw materials in the operating roasting conveyor machines.

Description of the experimental unit

The experimental unit for examination of kinetic parameters of drying, decarbonizing and sintering of iron ore charge in the flow of heating gases is developed and manufactured; its main components are presented in the **Fig. 1.**

To provide possibility of weighing of examined iron ore material, a dual-combustion motion route of heating gas is used; it compensates aerodynamic flow pressure on working areas. Balancing of gas flows is realized by dampers 8 and is controlled via pressure gradients on measuring orifices and in measuring areas.

Operating area is manufactured as a cylinder sleeve with perforated bottom, 100 mm in height and 50 mm in diameter, which is characterized by free motion inside gas circuit. The sleeves are connected with each other by a ceramic rod, located and swinging on the right balancing lever of automatic scales. A ring-shaped ferrite magnet is fixed on the left balancing lever; it is devoted to balancing of scales by electromagnetic solenoids, which are controlled by the scheme of weight loss compensation. Combined adjusting device, with a burner fixed directly to it, is mounted for regulation of the temperature and consumption of gas, which is sucked through working areas. When regulating plunger transfers in vertical direction, it leads to varying of consumption of heat-carrying gas, while when regulating plunger rotates, it finalizes in its temperature variation via mixing with air. Excessive hot gases are thrown into gas circuit, bypassing the operating area.

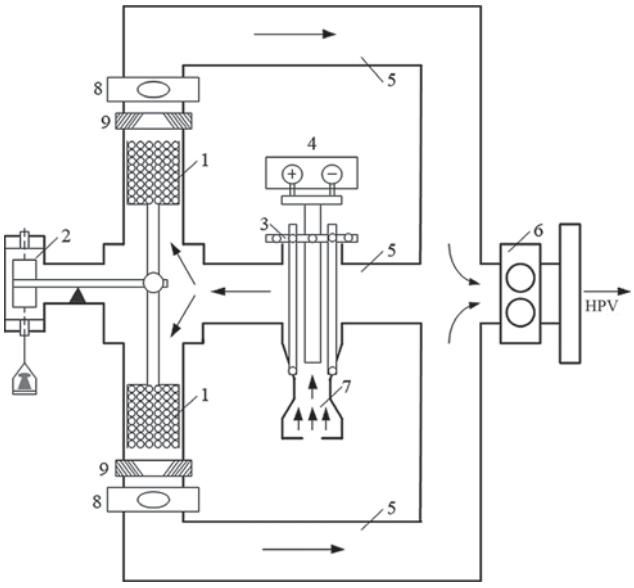

Fig. 1. Automatic thermogravimetric unit for examination of drying, decarbonizing and sintering kinetics for iron ore pellets in a flow of heat-carrying gas: 1 – measuring cells; 2 – automatic scales; 3 – adjusting device for operating procedures; 4 – automatic potentiometer; 5 – gas circuit; 6 – valve for rarefaction adjustment; 7 – burner; 8 – valve for balancing of gas flows; 9 – measuring orifices; → – gas flow direction.

The unit is presented by modular construction to provide access to the measuring cells. Gas circuits 5 are welded from stainless tubes with internal diameter 50 mm and are connected to air exhausting high-pressure ventilator VHP-5. The required rarefaction in gas circuits is regulated by the valve *6*.

The complete unit is fixed vertically on a frame, allowing to preset its levels to provide operation of automatic scales. Temperature measuring is carried out by thermocouples using automatic potentiometer *4*.

Operating principle of an automatic weight compensation device is based on balancing lever equalizing of scales by magnetic field.

To provide measurement of gas consumption, inclined micro-manometers and measuring orifices *9* are used. Rate of gas, which is sucked through a layer of examined material, is determined by pressure gradient in the measuring area.

Analysis of methods for determination of the efficient heat transfer coefficient during drying of iron ore pellets

Drying is understood as the process of moisture removal from a solid body via evaporation. It is possible only in the case when actual moisture concentration in a solid body is larger than equilibrium concentration, i.e. when partial pressure values of water vapours above the body surface and in the environment are equal. Difference between these values of partial pressure is a moving force of the drying process [13, 14].

When during capillary-porous bodies (including wet iron ore pellets), two periods of constant (first) and dropping (second) drying rate are underlined [15]. In this case drying rate is understood as varying of moisture content (relation of water mass to dry mass of a solid body) in time [16].

Moisture evaporation from the surface of a wet body during the first drying period occurs in the same way as from the free water surface and in accordance with the same laws [17, 18]. During this period the temperature of a drying body does not increase practically, because supplying heat is consumed for evaporation, and it continues until evaporation of all free (capillary) moisture [19, 20].

The second period starts from evaporation of bonded moisture, and drying rate is determined mainly by steam diffusion inside a wet body.

To calculate productivity of a drying area in the roasting conveyor machine, it is necessary to know the heat transfer coefficient α, which average in the volume of iron ore dispersed material layer.

During roasting period, i.e. when iron ore material is completely dried, the heat transfer coefficient can be calculated using the known formulas for stationary dense layer, which is blown through by a drying agent [21]. It is evident that these formulas can provide essential errors during the period of intensive drying, because they don't take into account heat transfer by water vapours (evaporation) [22]. In order not to complicate the calculation methods during roasting and drying, the efficient heat transfer coefficient is introduced usually for drying period; it can be determined from the following system of equations:

$$\frac{dQ}{dS\,d\tau} = \alpha\left(t_\infty - t_s\right) = \beta_p\left(p_{\text{sat}} - p_{\text{par}}\right)r = \frac{dW}{d\tau}\frac{V}{S}r\rho \qquad (1)$$

where α – efficient heat transfer coefficient, Wt/(m²·K); β_p – mass transfer coefficient, kg/(m²·s·Pa); p_{sat} – pressure of saturated water vapours at the temperature of drying material, Pa; p_{par} – partial pressure of water vapours, Pa; W– moisture content of wet material, (kg of water)/(kg of dry mass); r – specific heat of steam forming, J/kg; S – surface square, m²; V– volume, m³; ρ – density of drying material, kg/m³; t_∞– temperature of a drying agent, K; t_s– temperature of wet material surface, K; Q – heat amount, J.

It is followed from the presented relationships, that the efficient heat transfer coefficient α can be determined via three methods.

The first method is based on the following equation:

$$\frac{dQ}{dS\,d\tau} = \alpha\left(t_\infty - t_s\right) \quad \text{or} \quad \alpha = \frac{\Delta Q}{S\,\Delta\tau\left(t_\infty - t_s\right)} \qquad (2)$$

For a wet drying agent, ΔQ is determined via differences of enthalpies: $\Delta Q = \Delta i\ G = (i_{\text{ent}} - i_{\text{ex}})\,G - q_{\text{loss}}$, where i_{ent}, i_{ex}, – enthalpies at the entrance and exit of the layer, J/kg; G – consumption of a drying agent, kg/s; q_{loss} – heat losses in the environment, J.

Wet gas enthalpy can be determined via $i - d$ diagram, by moisture content d or relative humidity φ and temperature t.

Thus, this technique is required for measuring moisture content, temperature and drying gas consumption at the entrance and exit of the layer [23].

Moisture content can be determined experimentally via the temperatures of «wet» t_{w} and «dry» t_{dr} thermometers. The temperature t_{dr} is determined using a usual thermocouple, while to determine t_{w} it is necessary to keep thermocouple end at 100 % of humidity. For this purpose it is wrapped in a piece of gauze cloth or batiste, with its one edge placed in distilled water. If we know the temperatures t_{w} and t_{dr}, we can determine enthalpy of a drying agent via $i - d$ diagram.

Universality is an advantage of this method, it is valid for drying of both dispersed materials (e.g. iron ore charge) and capillary-porous materials (iron ore pellets) during whole drying period; necessity of measuring the humidity of a drying agent can be assessed ad disadvantage of this method, what complicates it significantly [24, 25].

The second method is based on the equation $\alpha(t_\infty - t_s) = \beta_p(p_{\text{sat}} - p_{\text{par}})r$. Principally it coincides with the first method, because if we know t_{w}, t_{dr}, we can determine $p_{\text{sat}} - p_{\text{par}}$ via $i - d$ diagram. However, for use of this method it is necessary to examine separately mass transfer for determination of the mass transfer coefficient β_p, what complicates the task substantially.

The third method is based on the equation

$$\alpha\left(t_\infty - t_s\right) = \frac{dW}{d\tau}\frac{V}{S}r\rho$$

To determine α via this method, it is necessary to measure permanently wet material weight, what can be implemented using the thermogravimetric unit (developed by the authors). Drying rate is determined in this case via relationship between moisture content and time. It is evident, that the first and second drying periods are characterized by different drying rate. When providing engineering calculation, we can neglect by the second period, because the main amount of moisture is removed during the period of constant rate [26].

This method can be simplified via approximation of the law of temperature gradient variation with the following relationship $t_\infty - t_{\text{s}} f(\tau)$; then the last equation can be interpreted in the following way:

$$\alpha f\left(\tau\right)d\tau = \frac{V}{S}r\rho dW$$

and after integration we shall obtain

$$\alpha = \frac{V}{S}r\rho\frac{\Delta W}{\int\limits_0^\tau f(\tau)d\tau}\ ,$$

where ΔW is variation of material weight. For the linear relationship $t_\infty - t_{\text{s}} = f(\tau)$ we shall obtain

$$\alpha = \frac{V}{S}r\rho\frac{2\,\Delta W}{b\tau^2}\ .$$

Necessity of continuous weighing can be avoided in this case, it is sufficient simply to seigh the sample in the beginning and the end of the experiment.

It can be concluded from the above-described brief analysis, that two independent techniques for determination of the efficient heat transfer coefficient are possible. They are based on the first and the third methods and use the data on enthalpy variation of a drying agent and weight variation of a wet iron ore sample. The designed unit can provide implementation of both techniques.

Error evaluation of variations of the efficient heat transfer coefficient

The first technique

The measurement error is calculated be the formula

$$\frac{\Delta\alpha}{\alpha} = \frac{\Delta i}{i} + \frac{\Delta G}{G} + \frac{\Delta S}{S} + \frac{\Delta t}{t_\infty - t_s}\ ,$$

where i – is determined via the $i - d$ diagram by the temperatures t_w and t_{dr}. Taking into account the fact that drying of iron ore raw material is carried out at the temperatures 20–300 °C, precision of enthalpy determination will be defined by precision of temperatures measurement.

Accuracy of temperatures measurement depends on accuracy of the dial of automatic potentiometer. The temperature gradient $\Delta\tau = 2.5$ °C is valid for the dial value 800 °C. The minimal value $t_w \approx 45$ °C is observed at the temperature $t_{dr} = 200$ °C, then

$$\frac{\Delta i}{i} = \frac{\Delta t_w}{t_w} + \frac{\Delta t_{dr}}{t_{dr}} = \frac{2.5}{45} + \frac{2.5}{200} \approx 7\% \ .$$

The drying time is determined by the speed of potentiometer band motion; $\Delta\tau = 2$ s for the speed 1800 m/s. Drying duration constitutes approximately 1,000 s (for pellets made from ore phosphorites), then

$$\frac{\Delta\tau}{\tau} = \frac{2}{1000} \approx 0.2\%$$

Surface and volume of pellets and charge can be measured using a caliper rule with accuracy 0.1 mm. It is evident that

$$\frac{\Delta S}{S} = 2\frac{\Delta d}{d}, \quad \frac{\Delta V}{V} = 3\frac{\Delta d}{d}$$

accepting d ≈ 10 mm, $\frac{\Delta S}{S} = 2\%$, $\frac{\Delta V}{V} = 3\%$.

Consumption of a drying agent is measured using pressure gradients on a measuring orifice. If this gradient will be measured by micro-manometer, accuracy of speed determination can be calculated via the formula:

$$\frac{\Delta w}{w} = \frac{\Delta G}{G} = \frac{\Delta H}{H} \ ,$$

where ΔH– accuracy micro-manometer dial division, H – height of liquid column. Maximal speed during drying of pellets $w_{max} = 1.5$ m/s.

To assess possibility of realization of this technique in the resented unit, let us consider correspondence of theoretical presentations, which are based on the Bernoulli equation for the model of non-compressing liquid. Thus, if we shall compare variation of flow rate at the valve for balancing of flow 8 with pressure variation at the entrance and the exit of this valve, then we can evaluate possible pressure gradient in the narrow cross section in accordance with continuity equation $w_1 S_1 = w_2 S_2$, where S_1 and S_2 are squares of cross sections at the entrance and the exit of the valve 8, while d_1 and d_2 are their diameters. As a result, if the diameters of the entrance and the exit vary by 5 times, we shall obtain corresponding variation of flow rate

$$w_2 = w_1 \frac{S_1}{S_2} = w_1 \left(\frac{d_1}{d_2}\right)^2 = w_1\ 25 = 37.5 \ \text{m/s},$$

what corresponds to the height of liquid column in micro-manometer with inclination coefficient K = 0.2, H ≈ 40 mm. Thereby

$$\frac{\Delta H}{H} = \frac{1}{40} = 2.5\% \ .$$

The second technique

It is evident that the difference is concluded in introduction of the error of weight measurement for drying material and excluding of the enthalpy error. Let us accept that $W = 100$ g, then

$$\frac{\Delta W}{W} = \frac{0.1}{100} \approx 0.1\% \ .$$

Accuracy can be assessed via the following formula:

$$\frac{\Delta\alpha}{\alpha} = \frac{\Delta V}{V} + \frac{\Delta S}{S} + \frac{\Delta b}{b} + 2\frac{\Delta\tau}{\tau} + \frac{\Delta W}{W} \ ,$$

and if $b = \frac{t_1 - t_2}{\tau_1 - \tau_2}$, then $\frac{\Delta b}{b} = \frac{\Delta t}{t_1 - t_2} + \frac{\Delta\tau}{\tau_1 - \tau_2}$, $\frac{\Delta\alpha}{\alpha} = 5.3\%$.

Thereby the second technique provides higher accuracy.

Taking into account non-stationary features of drying processes and, respectively, relationship between α and time, the final results should be processed via the least square method and presented in the form of criteria relationship: $Nu = A Re^m Pr^n$ where Nu – Nusselt criterion, Re – Reynolds criterion, Pr – Prandtl criterion.

Conclusion

The experimental thermogravimetric unit for research of kinetic parameters of the processes of drying, decarbonizing and sintering of iron ore charge in the flow of heating gases was developed and manufactured. It provides possibility of weighing of investigated iron ore material using double-combustion route of motion of heat-carrying gas for compensation of flow aerodynamic pressure. The experiments for determination of the efficient heat transfer coefficient during drying and roasting of sinter charge and iron ore pellets were carried out using the experimental thermogravimetric unit. These experiments were conducted for the temperature ranges and aerodynamic conditions of operating roasting conveyor machines during complicated energy-intensive chemical-metallurgical process of roasting of iron ore raw material in moving dense layer, with cross feed of heat-carrying gas.

The analysis of the methods of experimental determination of the efficient heat transfer coefficient during drying of sinter charge and iron ore pellets in the dense layer is presented. It was established that two periods are observed in the process of drying of iron ore materials: the periods of constant and decreasing drying rate, as during drying of capillary-porous bodies. Two methods for determination of the efficient heat transfer coefficient during roasting of iron ore raw materials are substantiated scientifically: the method of variation of enthalpy of heat-carrying gas (drying agent) and the method of variation of weight of wet iron ore sample. The designed experimental

thermogravimetric unit allows to implement both these methods. The error of variations of the efficient heat transfer coefficient during roasting of iron ore raw material is evaluated.

The conducted research and the developed thermogravimetric unit make it possible to determine substantially and then calculate thermal physical and heat and mass transfer coefficients in mathematical models [27, 28]. These models describe chemical and metallurgical processes of drying and roasting of iron ore materials in the dynamic dense layer with cross feed of heat-carrying gas in the conveyor of a roasting machine. Intensification of these processes allows to increase energy and resource efficiency of energy-intensive systems for thermal preparation of iron ore raw material.

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