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Oksanich I. G
PhD (technical science), associate professor,
Department of Automated and Information Systems
Kremenchug Mikhailo Ostrohradskyi National University
Kremenchug, Ukraine
Kovtun D.V
postgraduate
Kremenchug Mikhailo Ostrohradskyi National University
Kremenchug, Ukraine

EFFICIENCY IMPROVEMENT METHOD OF THE IRON ORE PELLETS PRODUCTION PROCESS CONTROL

Оксанич Ирина Григорьевна
кандидат технических наук,
доцент
доцент кафедры автоматизации и информационных систем
Кременчугский национальный университет
имени Михаила Остроградского
Кременчуг, Украина
Ковтун Дмитрий Владимирович
аспирант
Кременчугский национальный университет
имени Михаила Остроградского
Кременчуг, Украина

МЕТОД ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ ОПЕРАТИВНОГО УПРАВЛЕНИЯ ПРОИЗВОДСТВОМ ЖЕЛЕЗОРУДНЫХ ОКАТЫШЕЙ

Summary. The article describes the method of deepening the monitoring of the firing process of iron ore pellets, in particular, reducing the error of firing temperature measurement inside the rotary kiln. A mathematical model has been developed that describes the composition of the atmosphere inside the kiln and the significant factors that influence the temperature measurement error of a radiation pyrometer. The proposed model was checked for adequacy and the results obtained in the form of calculated values of temperature, standard error for each model value, 95% confidence interval of model values, and 95% confidence interval for average response. The proposed method will increase the efficiency of process control of the iron ore pellets production.

Аннотация. В статье рассматривается метод повышения мониторинга технологического процесса отжига железорудных окатышей, в частности уменьшение погрешности измерения температуры отжига в центре вращающейся печи. Разработана математическая модель которая описывает состав атмосферы внутри печи и определены факторы, которые влияют на погрешность измерения температуры радиационным пирометром. Выполнена проверка предложенной модели на адекватность, и полученны результаты в виде расчетных значений температуры, стандартной ошибки для каждого модельного значения, 95% -й доверительный интервал модельных значений и 95% -й доверительный интервал для среднего отклика. Предложенный метод позволит повысить эффективность оперативного управления процессом производства железорудных окатышей.

Key words: monitoring, process control, pellets, firing.
Ключевые слова: мониторинг, оперативное управление, окатыши, отжиг

Introduction.

In terms of information and material flows, the production process of iron ore pellets is characterized by a sufficiently large number of technological operations [1]. Most of these operations are sufficiently probabilistic because of the influence of uncontrollable factors on the production process. As a result, the pellet production process requires constant adjustment of process plans and process decisions [2].

Monitoring is an important part of the iron ore pellets production process control. It allows to detect in advance possible disturbances in the pellets production process to identify emergencies and, thereby, gives the opportunity to reduce the average production time of a batch of pellets.

Data obtained during the monitoring process can then be converted into diagnostic parameters. Based on these data takes place the identification of emergency situations. Monitoring allows to reduce the influence of operators' and technologists' errors on the control of technological process, which is especially important task in the production of iron ore pellets due to the complexity of the processes of preparation of the charge mixture (kiln feed) and firing of the pellets.

One of the important elements of the iron ore pellets production process is firing process. Increasing the depth of monitoring of this process will reduce or prevent the occurrence of abnormal situations, and thus increase the efficiency of the production process.

Analysis of recent research and publications.

For a long time, the issue of improving the quality of iron ore pellets has been addressed both, at domestic and foreign enterprises, but at present the methods used at enterprises do not fully solve the tasks of process control.

Modern literature presents systems for controlling the production of pellets, which include subsystems for monitoring process disturbances [3]. Work [4] describes an intelligent decision support system, which enables to collect and analyse the data in real time. A system for optimization of the sintering process based on neural networks was also developed, which prognoses the main indicators of process efficiency for its further optimization [5].

In the field of mathematical modeling of the production process of iron ore pellets are widely used works by Kitaev B.I. and his followers [6 – 8].

Many attempts have been made to create systems based, for example, on accumulated statistics (advisory systems, fuzzy logic, empirical models) or on theoretical fundamentals (eg, Isaev EA model theory) [9]. The complexity of creating such systems is explained by the insufficient amount of information and insufficient depth of monitoring of the elements of the technological process.

Highlighting previously unresolved parts of a common problem. Analysis of the literature has shown that the amount of information that enters the system of process control of the production of iron ore pellets plays a critical role in decision making. Of great importance is the information from the monitoring system for process parameters at all stages of production. At the same time, the depth of monitoring does not always let to make the right and timely decisions.

This problem can be caused by various reasons, such as the difficulty in controlling by sensors of some process parameters, the lack of accuracy of the sensors controlling some of the processes, etc. Such example is the temperature inside a rotary kiln, the measurement of which is the complicated element of the annealing process. Usually temperature monitoring is performed by the method of light spectroscopy based on partial radiation frequency pyrometer. At the same time, the transparency and contamination of the optical medium between the measuring object, in our case the burner firing zone, and the inspection window, through which the pyrometer optics focuses, significantly influences the accuracy of the pyrometer temperature measurement.

Therefore, the purpose of our study is to develop a method of in-depth monitoring of the temperature of the rotary kiln to improve the efficiency of

process control of iron ore pellets production.

Presenting main study material.

A rotary kiln firing pellets is a complex element of the annealing (firing) process. The firing of the pellets happens due to the radiation of the burner's flame and the hot refractory lining of the furnace, as well as the convection heat exchange between the gas flow circulating through the furnace, the refractory lining and the surface of the pellets' layer.

In works [10], authors developed a mathematical model and a method for calculating the temperature sensitivity of a pyrometer, which works on its own radiation of objects taking into account the reflected radiation of the surrounding background and the radiation of the optical elements of the scheme, which is described by the following formula:

$$\Delta T_{\text{sen}} = \frac{\pi\mu K_{\text{e}} 1 + U_o/U_{\text{i.s.}} + U_{\text{bg}}/U_{\text{i.s.}}\sqrt{ab\Delta f}}{A\varpi D * c_2 \left[\left(\frac{1}{T^2}\int_{\lambda_1}^{\lambda_2} S(\lambda)\tau_{\text{o}}(\lambda)\tau_{\text{a}}(\lambda)\tau_b(\lambda\varepsilon(\lambda)\lambda^{-1}M_{\text{e}}\lambda, Td(\lambda)\right)\right]} + \\ + \frac{1}{+\left(\frac{1}{T_{\text{bg}}{}^2}\int_{\lambda_1}^{\lambda_2} S(\lambda)\tau_{\text{o}}(\lambda)\tau_{\text{a}}(\lambda)\tau_b(\lambda)\rho(\lambda)\lambda^{-1}M_{\text{e}}(\lambda), T_{\text{bg}}d\lambda\right)} \tag{1}$$

Where μ – ratio «signal / noise»; Ke – the usage index of the radiation source of the reference source; U i.s. – interference signal equivalent to electrical noise; Uo and U bg – integral signals of internal optical and external background interference; a, b– linear dimensions of the sensitive area of the radiation receiver; Δf – the frequency band of the radiation receiver; A – the area of the incoming pupil of the pyrometer lens; ϖ – body angle of view of the lens; D*– the specific ability of the radiation receiver; c_2– Planck's second constant formula; T – thermodynamic (absolute) surface temperature of the object; S(λ) - relative spectral sensitivity of the radiation receiver; $T_{tl}(\lambda)$, $\tau_a(\lambda)$, $\tau_f(\lambda)$ – spectral transmittance coefficients towards the lens, atmosphere layer and spectral filter, respectively; ε(λ) – spectral coefficient of thermal radiation of the object surface; λ – length of the wave; Me (λ, T) – the spectral density of the energy brightness of a completely black body (CBB); T_{bg} – absolute background temperature (environment); ρ(λ) – spectral reflectance of the surface of the object under study; ε_o (λ) – spectral coefficient of thermal radiation of the surface of optical elements; Me(λ, T_{bg}) – spectral density of background's energy brightness.

In our case, considering that the temperature field on the surface of the background is heterogeneous, in formula (1) under the value Ubg we take the rms (room-mean-square) value of the interference signal (2):

$$\Delta U_{bg} = \sqrt{\Delta U_{bg}^2} = \sqrt{U - U_{bg}}^2, \tag{2}$$

and the values T_{bg} and Me(λ, T_{bg}) will make sense of the mathematical expectation against the background temperature field and the Planck function for the brightness of the CBB with the temperature Tbg.

Let's suppose that the function of distributing the temperature field over the surface of the atmosphere of a rotary kiln is some function P (T_{bg}), then we can write:

$$\overline{T_{bg}} = \int_{T_{1bg}}^{T_{2bg}} T_{bg} P T_{bg} dT_{bg} \tag{3}$$

$$\sigma^2 = \left(T_{bg} - \overline{T_{bg}}\right)^2 = \int_{T_{1bg}}^{T_{2bg}} \left(T_{bg} - \overline{T_{bg}}\right)^2 P T_{bg} dT_{bg} \tag{4}$$

In turn, the rms of the interference signal $\sqrt{\overline{\Delta U_{bg}^2}}$ we can get as follows:

$$\overline{\Delta U_{bg}} = \sqrt{\overline{\Delta U_{bg}^2}} = \frac{U_{i.s.} A \varpi D *}{K_e \pi \sqrt{ab\Delta f}} \left(\frac{c_2 \Delta T_{bg}}{\overline{T_{bg}}^2} \right) \times$$
$$\times \int_{\lambda_1}^{\lambda_2} S(\lambda) \tau_o(\lambda) \tau_a(\lambda) \tau_b(\lambda) \rho(\lambda) \lambda^{-1} M_e(\lambda, \overline{T_{bg}}) d\lambda. \tag{5}$$

Considering (1), the expression for pyrometer's temperature sensitivity of the true-temperature for a rotary kiln having the inhomogeneity of the background radiation temperature field, we can write:

$$\Delta T_{bg}^{(bot)} = \frac{\pi \mu K_e \left(1 + U_o / U_{i.s.} + \sqrt{\overline{\Delta U_{bg}^2}} / U_{i.s.}\right) \sqrt{ab\Delta f}}{A \varpi D * c_2 \times \left(\frac{1}{T^2} \int_{\lambda_1}^{\lambda_2} S(\lambda) \tau_o(\lambda) \tau_a(\lambda) \tau_b(\lambda) \varepsilon(\lambda) \lambda^{-1} M_e(\lambda), T d\lambda \right)} +$$
$$+ \frac{1}{\left(\frac{1}{\overline{T_{bg}}^2} \int_{\lambda_1}^{\lambda_2} S(\lambda) \tau_o(\lambda) \tau_a(\lambda) \tau_ф(\lambda) \rho(\lambda) \lambda^{-1} M_e(\lambda), \overline{T_{bg}} d\lambda \right)}. \tag{6}$$

The atmosphere of a rotary kiln can be considered as an inhomogeneous background that creates an obstacle and depends on the spectral coefficients of transmittance of the atmosphere layer, the spectral coefficient of thermal radiation of the combustion zone, the absolute temperature of the atmosphere of the rotary kiln, the spectral density of the atmosphere energy density. Respectively, we can assume that it obeys the law of expectation.

Let's rewrite expression (5) as:

$$\overline{\Delta U_{bg}} = U_{bg}(\overline{T_{bg}}) + \delta U_{bg} \tag{7}$$

where $U_{bg}(\overline{T_{bg}})$ and δU_{bg} are constant and variable components of interfering signl, that are equal to:

$$U_{bg}(\overline{T_{bg}}) = \frac{U_{п.е.} A \varpi D *}{K_e \pi \sqrt{ab\Delta f}} \int_{\lambda_1}^{\lambda_2} S(\lambda) \tau_o(\lambda) \tau_a(\lambda) \tau_b(\lambda) \rho(\lambda) \lambda^{-1} M_e(\lambda, \overline{T_{bg}}) d\lambda. \tag{8}$$

$$\delta U_{bg} = \frac{U_{п.е.} A \varpi D *}{K_e \pi \sqrt{ab\Delta f}} \left(\frac{c_2 \Delta T_{bg}}{\overline{T_{bg}}^2} \right) \int_{\lambda_1}^{\lambda_2} S(\lambda) \tau_o(\lambda) \tau_a(\lambda) \rho(\lambda) \lambda^{-1} M_e(\lambda, \overline{T_{bg}}) d\lambda. \tag{9}$$

Considering that, let's rewrite formula (1) as following:

$$\Delta T_{bg}{}^{bot} = \frac{\pi \mu K_e (1 + U_o / U_{п.э.} + U_{bg} / U_{i.s.}) \sqrt{ab\Delta f}}{A \varpi D * B} \tag{10}$$

where

$$B = c_2 \left[\frac{1}{T^2} \int_{\lambda_1}^{\lambda_2} S(\lambda)\tau_o(\lambda)\tau_a(\lambda)\tau_b(\lambda\varepsilon(\lambda)\lambda^{-1} M_e \lambda, Td(\lambda) + \atop + \frac{1}{{T_{bg}}^2} \int_{\lambda_1}^{\lambda_2} S(\lambda)\tau_o(\lambda)\tau_a(\lambda)\tau_{\mathbf{b}}(\lambda)\rho(\lambda)\lambda^{-1} M_e(\lambda), T_{bg} d\lambda \right]$$

Thus, it is possible to propose a method of taking into account the change in the sensitivity of the pyrometer under the influence of the atmosphere of the rotary kiln:

Set the temperature change range $\Delta T_{bg} = T_{bg2} - T_{bg1}$

and distribution function $P(T_{bg})$.

2. By formula (3), the mathematical expectation of the temperature field T_{bg} is calculated taking into account the distribution function.

3. By formula (4), the dispersion σ^2 for the temperature T_{bg} is calculated.

4. The obtained value T_{bg} is substituted into the formula for the brightness of the atmosphere with the spectral coefficient of thermal radiation ε (λ):

$$M_e(\lambda, T_{bg}) = \varepsilon_{bg}(\lambda) c_1 \lambda^{-5} \frac{1}{e^{c_2/\lambda T_{bg}} - 1}$$

5. By formulas (8) and (9) we can calculate values: $U_{bg}(T_{bg})$ and δU_{bg}.

6. By formula (7) we can calc the rms value of the interference signal ΔU_{bg}

7. By formula (10) we can calculate the change in the sensitivity of the pyrometer under the influence of the atmosphere of the rotary kiln ΔT_{sen}^{bot} .

To evaluate the influence of the kiln's atmosphere inhomogeneity at the value of temperature sensitivity of the true-temperature pyrometer [3], let's consider the following formula:

$$\Delta T_{sen}^{bot} = \Delta T_{sen} \frac{1 + U_o/U_{i.s.} + \Delta U_{bg}/U_{i.s.}}{1 + U_o/U_{i.s.} + U_{bg} \ /U_{i.s.}}. \quad (11)$$

Considering formula (7) we can express formula (11) as following:

$$\Delta T_{sen}^{bot} = \Delta T_{sen} \frac{1 + U_o/U_{i.s.} + (U_{bg}(T_{bg})/U_{i.s.} + \delta U_{bg}/U_{i.s.})}{1 + U_o/U_{i.s.} + U_{bg}/U_{i.s.}}. \quad (12)$$

Let's assume the following ratios:

$$U_{bg}(T_{bg}) \approx U_{bg};\ \Delta U_{bg}/U_{i.s.} >> (1 + U_0/U_{i.s.}),\ U_{bg}/U_{i.s.} >> (1 + U_0/U_{i.s.}),$$

then (12) we can rewrite as:

$$\Delta T_{sen}^{bot} = \Delta T_{sen} \left[1 + \frac{\delta U_{bg}}{U_{bg}(T_{bg})} \right] \quad (13)$$

Let's introduce value:

$$F(\Delta T_{bg}, T_{bg}) = 1 + \frac{\delta U_{bg}}{U_{bg}(T_{bg})}$$

then (13) will look like:

$$\Delta T_{bg}^{bot} = \Delta T_{bg} F(\Delta T_{bg}, T_{bg})$$

Function $F(\Delta T_{bg}, T_{bg})$ physically characterizes the influence of the background radiation temperature field parameters at the value of the pyrometer's temperature sensitivity.

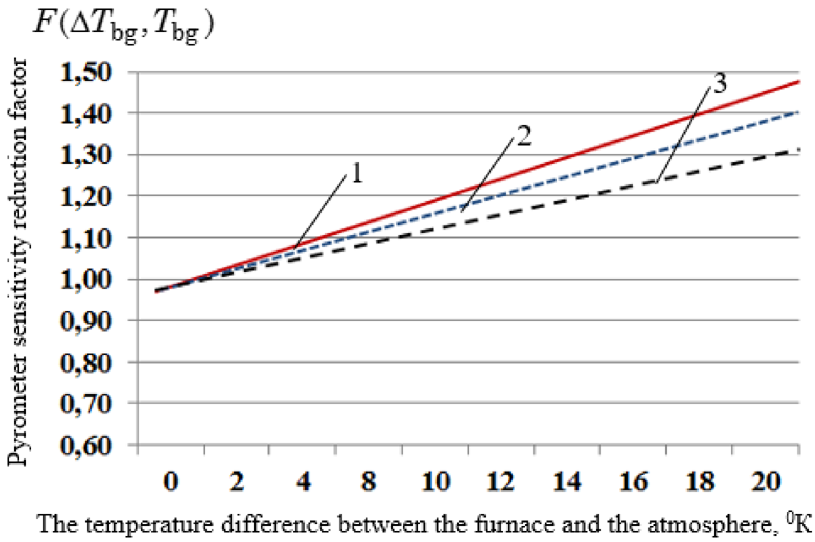

Fig. 1 – influence of the kiln's atmosphere radiation temperature field on the pyrometer's temperature sensitivity: 1 – temperature of the atmosphere 1470 ^0K; 2 – temperature of the atmosphere 1480 ^0K; 3 – temperature of the atmosphere 1490 ^0K.

Calculated in MathCad values of the pyrometer's sensitivity decrease coefficient are shown on fig. 1. The obtained dependence of the temperature sensitivity of the pyrometer on the temperature of the burner of the rotary kiln is shown on fig.2.

1. The burner temperature was measured without pellets in the kiln, i.e., there was no influence of kiln's atmosphere and dust;
2. The temperature of the burner was measured without rotation of the kiln, i.e. there was no influence of dust;
3. The temperature of the burner was measured during the rotation of the kiln, i.e. the effects of dust and atmosphere existed;
4. The temperature of the burner during the rotation of the furnace was measured, so there were effects of dusting and the atmosphere using the proposed method of taking into account the change in the sensitivity of the pyrometer under the influence of the kiln's atmosphere;

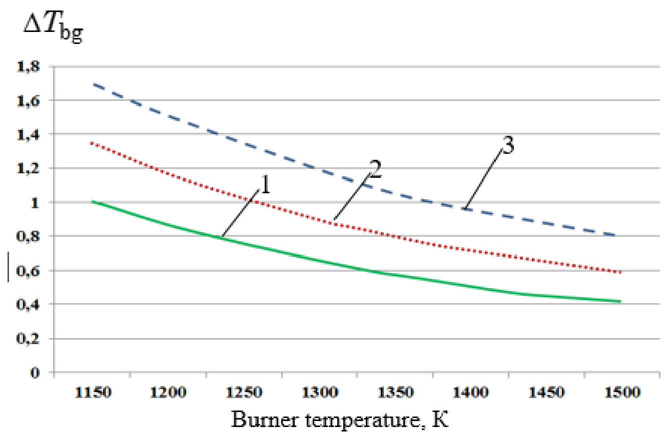

Fig. 2 – dependence of the temperature sensitivity of the pyrometer on the temperature of the burner: 1 – temperature of the atmosphere 1470 ^0K; 2 – temperature of the atmosphere 1480 ^0K;3 – temperature of the atmosphere 1490 ^0K.

The following scheme was used to evaluate model's adequacy:

Burner temperature values measured with a pyrometer without atmospheric influence and dusting were taken as an etalon.

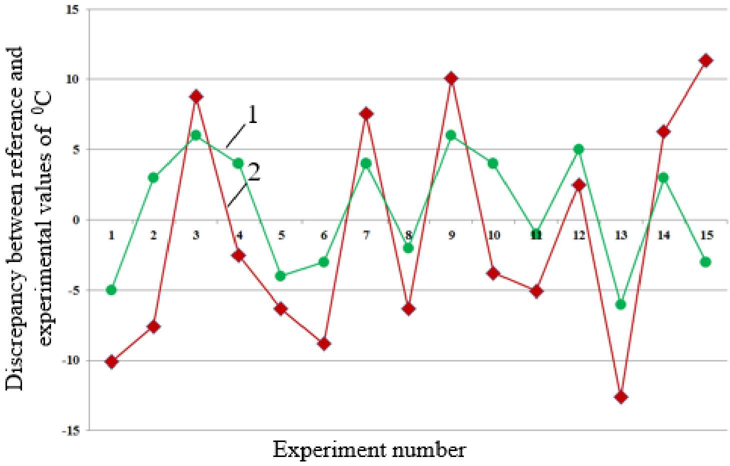

Fig. 3 – Deviations of the burner temperature etalon values from test values, ℃: 1 – temperature deviation with the obstruction of the atmosphere of the furnace; 2 - deviation of temperature under influence of restriction of the kiln's atmosphere using the proposed method of correction of temperature measurement.

The analysis of the obtained results shows that the discrepancy between the calculated and experimental data does not exceed ± 10 ° C, which is quite sufficient for the temperature of the combustion zone and for solving the problem of increasing the accuracy of measuring the combustion zone temperature of the rotary kiln firing pellets.

Deviations chart of the etalon values from experimental with the influence of the combustion zone atmosphere is shown on fig. 3.

Conclusions and suggestions.

The article proposes a method of deepening the monitoring of pellets firing process by reducing the error of measuring the firing temperature by taking into account the influence of the atmosphere of the rotary kiln, in order to increase the efficiency of operational control of the production of iron ore pellets. It is shown by simulation that, when exposed to the inhomogeneous field of thermal radiation of the background, as an obstacle to the operation of the pyrometer, its temperature sensitivity worsens. It is shown that physically the nature of the decrease in the sensitivity of the pyrometer is explained by two factors: the first factor is the "illumination" of the radiation receiver of the pyrometer constant component of the background radiation, the second factor is associated with the increase of the signal because of the interference due to the variable radiation component of the kiln's atmosphere.

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