On the issue of mathematical modeling of rotary kiln operation in order to reduce fuel consumption

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Abstract. In accordance with the operation principle of the rotary kiln of limestone and its shortcomings, the authors developed the foundations of a mathematical model. The ultimate goal of building algorithms for the proposed method is to reduce fuel consumption when using a rotary kiln. The paper proposes to use a mathematical model based on the method of energy balances. The scientific novelty is that for a rotary kiln for the first time it is proposed to use the method of energy balances by heating zones, depending on the type of fuel burned. The procedure of inputting initial data for mathematical modeling of heat transfer processes allows us to identify the largest heat fluxes in various zones of the furnace. After that, an optimization procedure is carried out using, among other things, objective functions, as well as nonlinear programming. In the end, such calculation algorithms allow us to make recommendations to reduce heat losses in a rotary kiln and a refrigerator, as well as to reduce specific fuel consumption.

1. Introduction
Rotary kilns have a number of advantages compared to shaft kilns. Firstly, this is a large unit capacity. Secondly, this is a uniform quality of the obtained lime at the degree of its roasting. Thirdly, this is a possibility of roasting small fractions of carbonate raw materials of any mechanical strength and high moisture. At the same time, rotary kilns have their drawbacks, for example, increased specific fuel consumption for firing, as well as high cost compared to a shaft furnace. The paper proposes a version of the problem of mathematical modeling of a rotary kiln in order to reduce fuel consumption. The fuel used is natural gas. In the case of the absence of natural gas, coke and blast furnace gases can be used if this does not harm the finished product [1]. These gases have a lower calorific value, so they require to be burned in larger volumes than natural gas. Sometimes liquid fuel is used as a backup fuel. Its calorific value is greater than the calorific value of natural gas. In rare cases, when it is possible to obtain a finished product of lower quality, pulverized solid organic fuel is used. The heat of its combustion depends on the type and grade of coal.

2. Description of the rotary kiln operation principle
The rotary kiln is a cylindrical steel drum lined from the inside and mounted obliquely on roller bearings (Figure 1). Raw materials can be dry or wet, depending on the destination of the final finished product. For the production of lime, the dry method is usually used, while for the wet method the raw material is chalky sludge [2].
Figure 1. Schematic diagram of a rotary kiln: 1 – mix feed, 2 – rotary kiln, 3 – electric drive shaft, 4 – fuel supply, 5 – unloading of hot product (hereinafter for cooling).

There are long rotary kilns and short kilns with heat exchangers behind the kilns. These heat exchangers are needed to cool the finished product. The clinker obtained at the exit of the furnace is to be ground in open or closed-loop pipe mills. The fineness of grinding is characterized by a residue on the sieve and is 8-12% for most cements. When exiting the furnace, the clinker has a temperature of about 1000 °C. Before serving in the cement mill, it must be cooled to at least 50-60 °C, otherwise the performance of the grinding unit will sharply decrease and the power consumption will increase. The cooling mode significantly affects the further technological process of cement production and the quality of the finished product. The rapid cooling of clinker contributes to the fixation in the glassy state of the clinker melt and the emergence of a predominantly defective crystalline structure of the main clinker minerals [3]. Therefore, fast cooled clinker is easier and more thinly grinded, which improves the quality of the cement.

Drum refrigerators are located under the discharge end of the kiln and therefore require the installation of kilns on high foundations. Drum cooler is a metal drum, rotating at a speed of 3 - 6 rpm from its own drive. In a drum cooler, clinker is cooled from 1000-1100 °C to 100-200 °C. Cooling air heated to temperature 300-400 °C, used as secondary air [4].

In contrast to the grate coolers, the air for cooling the clinker enters the drum coolers due to the vacuum generated by the furnace smoke exhauster. All cooling air is heated by clinker, enters the kiln and is used to burn fuel [5]. Thus, the amount of cooling air is equal to the amount of secondary air, therefore, there is no excess air in the drum coolers. Refrigerators for cooling lime are similarly arranged and work. The temperature mode of their work may vary.

The refrigerator is an inclined drum connected to the furnace by a vertical shaft through which the clinker is fed to cooling. Its working principle is as follows. The refrigerator is equipped with pouring elements, it is structurally not connected with the furnace, it has an independent drive, and tertiary air can be selected from it, and therefore it is applicable to modern furnaces with a calciner [6].

3. Setting a research problem. Scientific novelty. Practical significance.
In accordance with the operation principle of limestone rotary kiln and its shortcomings, it is advisable to develop a mathematical model with the ultimate goal of reducing fuel consumption. The paper proposes to put the method of energy balances in the basis of this mathematical model.

The scientific novelty is that for a rotary kiln it is first proposed to use the method of energy balances by heating zones depending on the type of burned fuel.

The practical significance of the work is to reduce fuel consumption for a rotary kiln, as well as the possibility of utilizing the heat of the finished product when building a mathematical model of a refrigerator behind rotary kiln.
4. Summary of scientific part of the study

Energy Balance Method (EBM) is a variation of finite volume method. It is one of the most promising numerical methods for solving multidimensional problems of heat transfer in moving media.

The main advantages of the method of energy balances include the possibility of its application to the calculation of complex thermal processes and the combination of simplicity and efficiency of the calculated ratios.

The object under study is conditionally divided into finite elements of an acceptable form, which make up the partitioning grid. The mathematical model of the object is transformed into a system of algebraic equations for the unknown temperatures of the nodal points (thermal centers) of the elements. The determination of the temperature field is reduced to solving the system of temperature equations together with the boundary conditions of heat transfer [7].

A distinctive feature of the EBM in the construction of the energy model of the process is that the state of the object is considered as a set of thermal states of individual elements that make up its design. It is usually assumed that within each element the temperature is the same and equal to the temperature of the thermal center at a given time [8]. Moreover, thermal centers are located inside the elements. This allows you to create a simple and convenient for the study model of the process implemented on a computer with minimal computational costs and a fairly high degree of accuracy.

According to the first law of thermodynamics for an arbitrarily taken body volume V, we can write the equation of energy flow in the form [9]:

\[ Q_v \cdot Q_f = dI / dr - V \cdot dP / dr. \]  

(1)

Heat flux due to the action of internal heat sources with power \( q_v \):

\[ Q_v = \int_v q_v dV. \]  

(2)

Heat flux from the volume V under consideration through the body surface \( F \):

\[ Q_f = \int_f \bar{q} (A) \bar{n} (A) dF = \int_f Q_n (A) dF, \]  

(3)

where \( q_v (A) \) – vector projection \( \bar{q} (A) \) of heat flux density on outward normal \( \bar{n} \) at point \( A \) to the surface of the body \( F \).

The change in enthalpy of the body over time:

\[ \tau \frac{dI}{dr} = \int C_p' \frac{dT}{dr} dV, \]  

(4)

where \( C_p' \) – body specific heat capacity at constant pressure; \( \tau \) – body temperature.

From the Ostrogradsky-Gauss theorem it follows that:

\[ Q_f = \int_f q_n (A) dF = \int_v \text{div} \bar{q} \ dV. \]  

(5)

If we neglect the energy expended on the temperature deformation of body, and considering \( P=\text{const}, \) \( dT/dV = 0 \), then equation (1) takes the form:

\[ \int_v q_v dV - \int_f q_n (A) dF = \int_v C_p' \frac{dT}{dr} dV. \]  

(6)

Integral equation (6) is a generalized mathematical formulation of heat conduction problems.

Then the standard procedure of mathematical modeling is applied using an explicit or implicit difference scheme.

Taking into account (3) equation (6) can be written:

\[ \int_v (\text{div} \bar{q} - q_v + C_p' \frac{dT}{dr}) dV = 0. \]  

(7)

Considering the process characteristics as continuous functions of coordinates, the differential heat equation follows from equation (7):

\[ C_p' \frac{dT}{dr} = \text{div} (\lambda \ \text{grad} T) + q_v, \]  

(8)

\[ C_p' \frac{dT}{dr} = \frac{d}{dr} \left( \frac{\lambda}{\sigma} \frac{dT}{dr} \right) + \frac{d}{dy} \left( \frac{\lambda}{\sigma} \frac{dT}{dy} \right) + \frac{d}{dz} \left( \frac{\lambda}{\sigma} \frac{dT}{dz} \right) + q_v. \]  

(9)
5. Conclusion
The procedure of inputting initial data for mathematical modeling of heat transfer processes allows us to identify the largest heat fluxes in various zones of the kiln. After that, an optimization procedure should be carried out using, among other things, objective functions, as well as nonlinear programming. In the end, such calculation algorithms allow us to make recommendations to reduce heat losses in a rotary kiln and a refrigerator, as well as to reduce specific fuel consumption.

To increase the intensity of heat exchange between the gas flow and the material in the cold part of the furnace, built-in heat exchangers are installed. They can be made as chain, shielding, and cell type. As experiments show, conducted on rotary kilns, chain curtains are always the best option. The proposed mathematical model can take into account any variants of heat exchangers.

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References
[1] Ingrao C, Selvaggi R, Valenti F, Matarazzo A, Pecorino B and Arcidiacono C 2019 Life cycle assessment of expanded clay granulate production using different fuels Resources, Conservation and Recycling 398-409
[2] Incropera F.P. et al. 2007 Fundamentals of Heat and Mass Transfer, 6th Edition (John Wiley & Sons, Inc) 999 p
[3] Belgacem S, Galai H and Tiss H 2019 From a mineralogical analytical view to a mechanism evaluation of cement kiln rings Eng. Failure Analysis 95 289-299
[4] Osintsev K, Prikhodko I, Pashnin V 2018 Increasing efficiency of boiler unit by installation of gas-piston micro central heat power plant IOP Conf. Ser.: Earth and Envir. Sci. 194 1-5
[5] Chatterjee A 2011 Chemistry and engineering of the clinkerization process – Incremental advances and lack of breakthroughs Cement and Concrete Res. 41 (7) 624-641
[6] Yang M-C, Wang J-Z and Sun T-Y 2018 EMD-based preprocessing with a fuzzy inference system and a fuzzy neural network to identify kiln coating collapse for predicting refractory failure in the cement process Int. J. of Fuzzy Systems 20(8) 2640-2656
[7] Ying Z, Lixin C, Qiao L, Guozan C and Xuchu Y 2018 Simulating the process of oxy-fuel combustion in the sintering zone of a rotary kiln to predict temperature, burnout, flame parameters and the yield of nitrogen oxides Chemistry and Technology of Fuels and Oils 54(5) 650-660
[8] Osintsev K, Prikhodko I and Zavyalova M 2018 Methods for improving energy efficiency of air handling unit using factor analysis of data IOP Conf. Ser.: Earth and Envir. Sci. 194 1-4
[9] Dumont G, Belanger P 1978 Steady-state study of a titanium dioxide rotary kiln Indust. & Eng. Chem. Proc. Design and Developm. 17(2) 10-14