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Modeling the thermal operation of a petroleum coke-calcining unit

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The article describes the development of a mathematical model of thermal state of the unit lining for calcining petroleum coke. Determination of the temperature fields of the lining will allow you to control the quality and volume of the resulting technological product, assess heat losses from the surface of the unit to the environment, and observe thermal conditions during start-up operations and shutdowns. To check adequacy of the model, calculations of temperature on the inner surface of lining of the coke calcination furnace were carried out during the heating process. The analysis of the given graphs shows that the developed mathematical model is adequate. On average, difference between thermocouple readings and calculated values does not exceed 5%. Further use of the developed mathematical model will be to create a computational complex for evaluating temperature fields along the entire length of rotary kilns for calcining petroleum coke.

Keywords: Lining, temperature stresses, mathematical model

INTRODUCTION

Improving the thermal performance of the linings of high-temperature units is a very wide range of measures aimed at increasing their energy efficiency. It, in turn, can be broken down into three components:

- rationalization of the lining design;
- the use of new refractory materials;
- improvement of thermal modes of lining operation.

Rationalization of the lining design may imply: a change in the profile of the inner surface of refractories, the thickness of the lining layers, the geometry of the refractory itself, etc.

The change in the profile of the inner surface of the lining is made based on operational data, which analyzes the parts of the lining that are subject to the greatest wear. This can be caused by various reasons - the effect of chemically aggressive slags, metal jets during its discharge, etc. Selection of refractory thicknesses corresponding to their actual operation in a given place of the lining, according to [1], can increase the lining durability by 10-15%.

A change in the thickness of the lining layers, calculated for specific conditions, can lead to a decrease in heat losses by 10-15%. So, in [2], to reduce heat losses, a combined lining was created, consisting of chamotte and additional fibrous heat-insulating material (mullite-silica wool). At the same time, a cell filled with heat-insulating material is formed between the refractory and the furnace body.

Replacing the lining material with another can also be attributed to the rationalization of the design [3-6]. In such cases, the non-load bearing lining layer (usually made of molded refractories) is replaced with an insulating layer of fibrous materials. The use of fibrous materials for the lining of furnaces allows, in comparison with brick lining, to reduce heat losses through the lining by 20-30%, to reduce several times the heating time of the furnace and the duration of installation of the lining, to save energy resources up to 45% with periodic stoppages of the furnaces [7]. Heat treatment of refractory raw materials also has a significant effect [8].

The use of geometrically rational refractories also affects the life of the lining. Classic shapes of molded refractories - straight and wedge bricks are not optimal in terms of uniformity of stress. In this respect, the hexagonal shape of products is more preferable, therefore, products in the form of hexagonal prisms should find application in ferrous metallurgy units [9].

Improving the thermal operation of the lining is undoubtedly the most cost-effective way to improve the thermal operation of the linings. In this case, there is no need to purchase new refractories or to change the design of the unit itself. Initially, each high-temperature unit has thermal schedules for heating up and operating the unit. These charts are "factory" and are usually designed to ensure that the rate of temperature change does not exceed the rates recommended by the manufacturer for lining materials. Naturally, these graphs are general and do not reflect the specifics of the operation of a

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particular unit. Thus, this does not take into account the thickness and number of lining layers, the presence of cooling, wear of the lining during start-ups from repairs with partial replacement of the lining, etc. , but also to an increase in the working campaign of the units (by reducing the heating time and downtime).

The first stage in improving the thermal operation of the lining will be the creation of a model of the thermal operation of the lining [10, 11].

Modeling the thermal operation of a petroleum coke-calcining unit is reduced to calculating the temperature field inside the furnace during the unit heating up. The problem of determining the temperature fields in the construction of a unit with flat walls and one layer of refractory lining material is widely presented in the literature [12, 13]. Meanwhile, there is a wide range of high-temperature installations for which these developments are not applicable. These are tubular rotary kilns and, in particular, for refinery coke calcination.

From the standpoint of determining the thermal state, these furnaces can be attributed to one group according to the following parameters. They have a considerable length (from 60 to 100 meters) with a diameter of 3 to 5 meters. The inner part of the metal cylindrical body is covered with a layer of refractory material, usually made of refractory bricks. The furnace is installed at an angle of 3 to 5° to the horizon and is capable of rotating at a speed of up to four revolutions per minute. Due to the tilt, the rotation of the furnace facilitates the movement of technology material from the feed end to the discharge end. Rotary kilns work on the principle of counterflow - raw material is fed from one side, and fuel is burned from the opposite. As a result, the gases formed during fuel-burning move towards the flow of material, directly carrying out the heat exchange process.

PROBLEM FORMULATION

As a rule, tubular rotary kilns have an internal surface temperature control sensor - this is a thermocouple installed in the most important (technologically) zone. But the installed thermocouple makes it possible to control only a part of the unit (only one zone) and does not allow controlling the temperature condition of the process material along the entire length of the unit. It is technically difficult to install temperature sensors in each zone.

Determining of temperature fields in the furnace during its operation allows you to have information for solving a number of problems. Firstly, it is the quality of the resulting technological product. Based on the main thermophysical properties of the product (humidity, volatile-matter content, etc.), it is necessary to maintain the calculated thermal condition, which can be controlled by the temperature of lining [14, 15, 16]. Secondly, it is volume of the technological product. When maintaining the optimal thermal condition, the furnace will have not only maximum productivity, but also minimum energy consumption per unit of production [17]. Thirdly, control of temperature state of lining allows not only to estimate temperature losses from surface of unit to the environment, but also to reduce them at the design stage when considering various options for refractory materials for their use in the lining [18, 19]. Fourth, compliance to thermal conditions during operation and shutdowns allows to extend the life of the lining, which leads to significant savings [20, 21, 22]. As a result, control and compliance with thermal conditions during the operation of ring rotary kilns is an important step in the policy of energy saving.

Modern technical means make it possible to conduct a continuous process of monitoring the thermal state of the lining using thermal imaging. This allows to solve a number of the above-mentioned problems: control of the thermal regime and losses from the surface of the high-temperature unit [23]. To solve other problems, a mathematical apparatus is needed that allows calculating temperature fields not only over the thickness of the lining (which is important for stationary processes), but also in time (for non-stationary processes). Installation of a number of temperature sensors for measuring the temperatures of the inner surface of the lining (by zones) is technologically difficult and significantly reduces the reliability of the rotary kiln. As the result, the task is to develop a mathematical apparatus that makes it possible to calculate the temperature fields of the masonry in a stationary and non-stationary mode using the initial temperature data: the temperature of the process material and the outer surface of the lining.

The mathematical treatment of this process is generally represents a system of partial differential equations. What is more, the integration of this system is a difficult task, the solution of which requires special mathematical support and high power of computer facilities.

Consider the thermal state of ring lining of the coke calcination furnace, presented as a long hollow cylinder. The cross section of the furnace (Fig.1) is a double-layer ring. Let us introduce the following assumptions:

- Thermophysical and mechanical properties of each lining layer are different and constant within each layer;
- Temperature of inner surface is taken equal to the temperature of technological material;
- At the boundary between layers - equality of heat current;
- The heat transfer law is set on the outer surface of the furnace body.

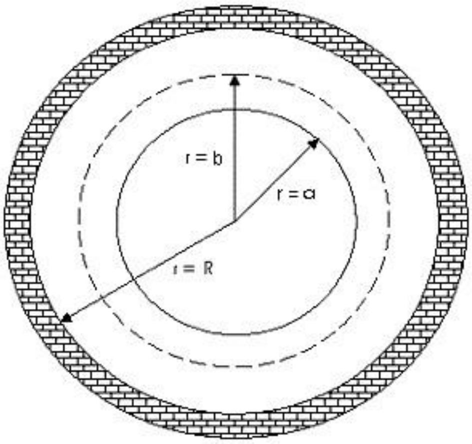


Fig.1. Calculation scheme of the furnace lining

METHODOLOGY OF THE RESEARCH PRACTICE

Mathematically, taking into account the accepted assumptions, the problem is formulated in a certain way. Let us write the equation of heat conduction in a cylindrical coordinate system with a radial temperature distribution:

$$\text{for the 1 layer } \frac{\partial T_1}{\partial t} = a_1 \cdot \left(\frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T_1}{\partial r} \right), \tag{1}$$

$$\text{for the 2 layer } \frac{\partial T_2}{\partial t} = a_2 \cdot \left(\frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T_2}{\partial r} \right), \tag{2}$$

where

$\frac{\partial T}{\partial t}$ – temperature change over time, ^{o}C;

$\frac{\partial T_2}{\partial r}$ – temperature change along the radius of the furnace, ^{o}C.

with initial

$$T(r,t)\big|_{t-0} = T_0 = const \tag{3}$$

and boundary conditions:

$$\text{provided } r = a; \quad t > 0 \quad T_P = T_R \tag{4}$$

$$r = b;\ k_1 \cdot \frac{\partial T_1}{\partial r} = k_2 \cdot \frac{\partial T_2}{\partial r} \tag{5}$$

$$r = R;\ k \cdot \frac{\partial T}{\partial r} - h \cdot \left(T_{amb} - T \right) = 0 \tag{6}$$

where:

T_P – temperature of the medium in the furnace, ^{o}C

T_R – temperature of the inner surface of the furnace, ^{o}C

r – furnace lining radius, m;

$r = a$ – inner surface of the lining, m;

$r = b$ – border of lining layers, m;

$r = R$ – outer surface of the lining, m;

k – thermal conductivity of the refractory material, W / (m · K);

h– heat transfer coefficient, W / (m^2 · K);

T_{amb} – ambient temperature, ^{o}C

It is of interest is an algorithm for calculating the temperature field of the lining, involving the use an implicit difference scheme [24, 25, 26], based on the application of the sweep method under boundary conditions on the outer surface of the furnace. This method has several advantages. Firstly, when calculating, the count starts from the outer boundary and, therefore, the computational process can be completed when the temperature at the outer boundary satisfies some condition. As the conditions for using the temperature of the furnace body, obtained by measurements. Secondly, the implicit difference scheme is stable at any time and space steps.

The initial equation for the implicit difference scheme will be:

$$\frac{\mathrm{T}_{\mathrm{n}}^{\mathrm{k+1}} - \mathrm{T}_{\mathrm{n}}^{\mathrm{k}}}{\Delta \mathrm{t}} = \frac{\mathrm{a}\left(\mathrm{T}_{\mathrm{n-1}}^{\mathrm{k+1}} - 2\mathrm{T}_{\mathrm{n}}^{\mathrm{k+1}} + \mathrm{T}_{\mathrm{n+1}}^{\mathrm{k+1}} \right)}{(\Delta \mathrm{x})^2} \tag{7}$$

where:

Δx – coordinate step, m;

Δt – time step, s;

a_t – temperature conductivity coefficient, m^2/s;

T_n^{k+1} – lining temperature at a point along coordinate n at time k+1, °C.

Transform this equation as follows:

$$-h^2 \cdot T_i^k = a\Delta t T_{i-1}^{k+1} - (2a\Delta t + h^2)\cdot T_i^{k+1} + a\Delta t T_i^{k+1}, \tag{8}$$

$$-T_i^k = \frac{a\Delta t}{h^2}\cdot T_{i-1}^{k+1} - \left(\frac{2a\Delta t}{h^2}+1\right)\cdot T_i^{k+1} + \frac{a\Delta t}{h^2}\cdot T_{i+1}^{k+1}$$

Set $A = B = \frac{a\Delta t}{h^2}$ and C=1+2A, then the equation (16) will be

$$-T_1^k = AT_{i-1}^{k+1} - CT_i^{k+1} + BT_{i+1}^{k+1} \tag{9}$$

The sweep formulas, in this case, will be represented by the ratios:

$$T_i^{k+1} = \gamma_{i+1}\cdot T_{i+1}^{k+1} + \beta_{i+1} \tag{10}$$

$$\gamma_{i+1} = \frac{A}{C - \gamma_1 A} \tag{11}$$

$$\beta_{i+1} = \frac{A\beta_i + T_i^k}{C - \gamma_i A} \tag{12}$$

$$\gamma_1 = 0,\ \beta_1 = T_n \tag{13}$$

The temperature value T_{i+1}^{k+1} is found from the boundary conditions at the outer boundary.

EXPERIMENT ANALYSIS

To check the adequacy of the model, the temperature was calculated on the inner surface of the coke calcining furnace during the heating process.

Calcining petroleum coke is the process of heating crude petroleum coke to 1250÷1350°C. At the same time, in the entire mass of coke, processes of structural change occur with the removal of hydrogen, which is released in the form of methane and other hydrocarbon compounds and burns in calcining and afterburning furnaces. The main goal of the calcining process is to improve the physical and chemical properties of coke, such as electrical resistance, true density, oxidizability and reactivity, as a result, the product acquires the necessary qualities.

Coke is calcined in a rotary kiln 65 m long and 3.47 m in diameter, which is installed at an angle of 4° to the horizon and is capable of rotating at a speed of up to two revolutions per minute. Combustion of volatile substances and fuel (fuel oil) during the calcination of petroleum coke produces a large amount of high-temperature flue gases that contain volatiles and a small proportion of fine coke particles. 50-60% of volatiles are burned in the calcining furnace, the rest enter the afterburner together with flue gases. After water evaporation and removal of volatile components, the coke is heated to 1350 °C. Moreover, its molecular structure takes on a more organized form with a clear crystal lattice. In response to the physical and chemical processes occurring with the raw material, the consumer properties of coke are improved. The time of the complete coke calcination cycle from loading to unloading is at least 45 minutes.

In accordance with the developed mathematical model, the temperature calculated over the lining cross-section during the heating process. Fig.2 shows graphs of heating at characteristic points along the cross-section of the lining during the first 24 hours: on the inner surface, in the middle and on the outer surface of the lining.

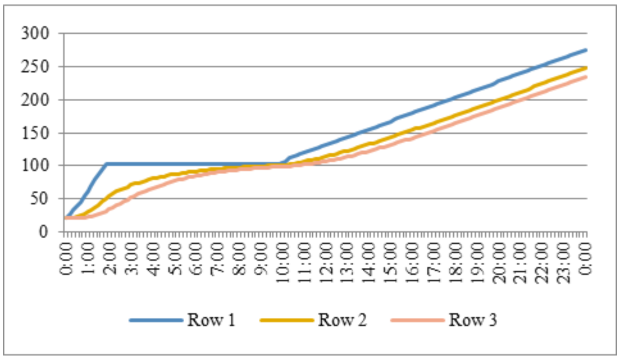


Fig.2. Graphs of heating at characteristic points along the section of the lining in: row 1 - on the inner surface, row 2 - in the middle, row 3 - on the outer surface of the lining

The analysis of the graphs obtained shows that the heating process during the first one hour and forty minutes proceeds at a high speed, which reflects the change in the temperature of the inner surface. High heating rates across the lining thickness begin at fifty minutes (for the middle of the lining) and one hour and forty minutes for the outer surface. Horizontal section of the heating curve, corresponding to a temperature of about 110°C, is necessary to remove moisture from the lining. At a constant heating rate of the lining by the time 9 h 10 min, we have an almost stationary temperature field.

To check the adequacy of mathematical model and calculations performed, a graph of the dependence of temperature inner surface of the lining on time was built. The obtained values for temperature of the inner surface for comparison with the actual temperature of the surface are shown in Fig.3.

The heating-up schedule of the furnace after major overhaul (heating section up to 500 °C) is shown in Fig.3. Row 1 - a graph based on the readout of a thermocouple installed in the furnace lining, row 2 - a graph based on the results of calculations based on the developed mathematical model.

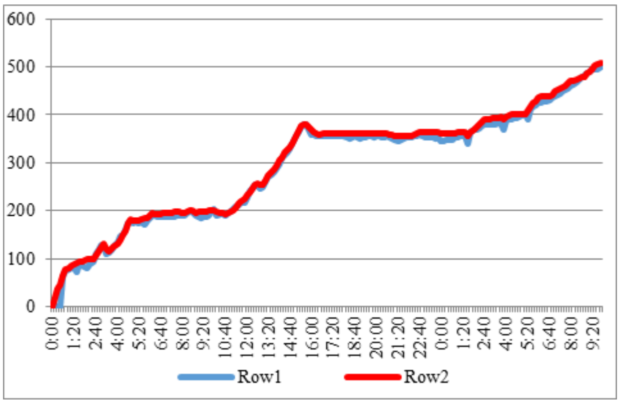


Fig.3. Graphs of heating the furnace after major overhaul

The analysis of the given graphs shows that the developed mathematical model is adequate. On average, the difference between the thermocouple readouts and the calculated values does not exceed 5%. Large values of the difference between the readings of the two graphs, as a rule, to areas of a sharp increase or decrease in temperature. This can be explained by the delayed action of the temperature measurement process.

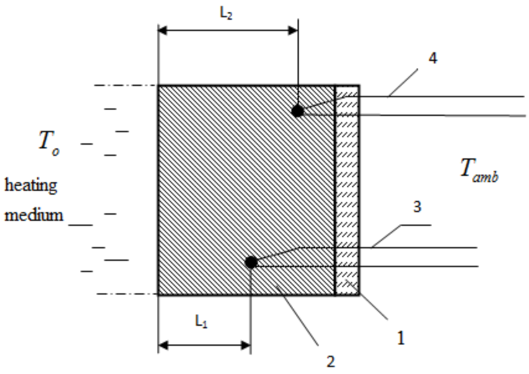
The developed mathematical model makes it possible to calculate the temperature fields of the masonry in a stationary and non-stationary mode using the temperature of the technological material and the outer surface of the lining. Using the developed technique, it is possible to obtain the temperature distribution over the lining cross section during the heating of any zone of the furnace, while the initial data for the calculation will be the temperatures indicated above. Measuring the temperature of the outer surface of the furnace is not technically difficult - it can be measured by direct measurement with the installation of a sensor between the steel body and the lining. Also, this temperature can be equated to the temperature of the metal body (taking into account the high thermal conductivity of steel), and the temperature of the body metal can be measured in a non-contact way (pyrometer, thermal imager).

It remains important to determine temperature of the inner surface, or temperature of the technological material in this zone. Technically, not every zone can accommodate a temperature sensor to measure the parameters of the inner surface. The thermocouple port, which runs through the entire lining, is a hazard at high process material temperatures due to possible leakage and material escaping through the sensor port.

Taking temperature of the process material, focusing only on finding it in a specific zone of the furnace, can lead to high calculation errors. This is due to the fact that within one zone of the furnace, the temperature of the process material can change by 300 ÷ 400 °C.

To increase the accuracy of calculating temperatures, it is proposed to use a method for determining the thermal state of the lining, which allows, by taking temperature readings from partially buried temperature sensors, to obtain the temperature distribution in the lining section according to the developed mathematical model.

The lining of the high-temperature unit is a wall consisting of a casing 1 and a layer of heat-insulating (or refractory) material 2 (Fig.4). Unit lining contains a temperature sensor 3 at a distance L1 from its inner surface and a temperature sensor 4 at a distance L2 from its inner surface. Inside the heating unit there is a working medium with a temperature T_o. Outside, the ambient temperature is T_{oc}.



T_o – heating medium temperature, °C; T_{amb} – ambient temperature, °C; 1 – the unit’s cover; 2 – refractory material; 3, 4 - thermocouples

Fig.4. Implementation diagram of the method for determining the thermal state of the lining

In the process of laying lining of thermal units, temperature sensors are installed in the lining at specified distances from its inner surface. The number of sensors and the distance from the inner surface are selected based on operational limitations associated with the possibility of emergency situations (leakage, etc.).

From the moment the heating unit starts heating (τ_0), the heating time is counted. For calculations, the step along the Δy coordinate is determined, that is, distance between two nearest points of heating unit lining, at which the temperatures will be determined. Why geometrically divide the wall lining by thickness into such a number of equal sections so that the temperature measurement points by sensors 3 and 4 fall on boundaries of sections between two nearest points of coordinate step.

Then the time step $\Delta\tau$ is determined, that is, the time interval after which the temperatures will be determined over the lining cross section at the selected points.

To determine the temperature fields of the lining of an industrial unit at time τ_1 in the process of non-stationary thermal conductivity, temperature readings are taken by temperature sensors 3 and 4 (T_3 and T_4, respectively).

Further, they are initially set by the temperature of the heating medium T_o. The initial value of this temperature is taken as the lowest possible (under the given heating conditions). Then, the temperature values are calculated over the lining section of thermal unit for the time point τ_1 according to proposed mathematical model.

If at the considered moment of time, calculated temperature at a point at a distance L_1 from the inner surface of lining turns out to be equal to T_3 and the temperature at a point at a distance L_2 from inner surface of lining is equal to T_4, then the calculation is stopped. In this case, the obtained temperature distribution over the lining cross section will be the desired one.

If this condition is not met, set a different temperature T_o and repeat the calculation again.

The more temperature sensors are located along thickness of lining, the smaller error in determining temperature field. The minimum number of temperature sensors is dictated by operational limitations associated with the possibility of emergencies.

As a result, the use of this method will increase the accuracy of calculating the temperature distribution over the lining cross section for developed mathematical model. In this case, only the installation of partially recessed temperature sensors in various zones of the furnace is additionally required.

Approbation of the method for determining the thermal state of the lining on a physical model in laboratory conditions has shown that the mathematical model can be applied in practice. (Fig.5).

The laboratory research facility consists of a muffle furnace without a door in which the investigated refractory material is placed instead of that furnace door. Two thermocouples are placed in the refractory according to the above procedure. A secondary device is used to measure and record the temperatures of the refractory and the environment. Thus, the material heated on one side by the heat space of the furnace and cooled by the environment on the other side is a physical model of the wall of the high-temperature unit.

To increase the accuracy of calculations in the study of refractories from working units, the values of the thermal conductivity coefficient were used, taking into account the impregnation of refractories with a working medium [27].

Fig.5. Approbation of the method for determining the thermal state of the lining on a physical model in laboratory conditions

The studies carried out show that the error in determining the temperature over the cross section of the lining during heating in accordance with the method for determining the thermal state of the lining does not exceed 10% [28], which indicates the possibility of using these developments in industrial conditions.

CONCLUSION

A mathematical model of the thermal state of a high-temperature unit has been developed, which makes it possible to control the internal temperature of the furnace, both in the heating mode and in the operation mode. Approbation of the technique during the heating of the coke calcination unit allows us to speak about the sufficient reliability of the data obtained.

The use of this mathematical model makes it possible to control technological processes during the processing of the initial raw material in the furnace, avoiding excess energy consumption.

Further use of the developed mathematical model will be to create a computational complex for assessing temperature fields along the entire length of rotary kilns for calcining petroleum coke.

REFERENCES

1. D.V. Koryukov, V.V. Levchuk, A.A. Metelkin, O.Yu Sheshukov, I.V. Nekrasov, L.A., Marshuk, Methods of increasing the durability and reliability of the lining of vacuum chambers in OJSC "NTMK", *Theory and technology of metallurgical production*, pp.48-51 (2010).
2. A.A. Markus, Simulation of thermal processes in tubular rotary sintering furnaces. Abstract of a dissertation for the degree of candidate of technical sciences. National University of Mineral Resources Saint Petersburg (2014).
3. Kuo Lin, Zhongjie Shen, Qinfeng Liang, Jianliang Xu, Haifeng Liu, Modelling study of characteristics of heat transfer and structural optimization of refractory layer in an entrained-flow gasifier, *Applied Thermal Engineering*, Volume **168**, 114830, (2020), https://doi.org/10.1016/j.applthermaleng.2019.114830.
4. Bo Ren, Yawei Li, Mithun Nath, Qinghu Wang, Yibiao Xu, Enhanced alkali vapor attack resistance of bauxite-SiC refractories for the working lining of cement rotary kilns via incorporation of andalusite, *Ceramics International*, Volume **44** (18), pp. 22113-22120, (2018), ,https://doi.org/10.1016/j.ceramint.2018.08.323.doi.org/10.1016/j.ceramint.2018.08.323.
5. Shuang Shi, Pengting Li, Zhilin Sheng, Dachuan Jiang, Yi Tan, Dengke Wang, Shutao Wen, H.M. Noor ul Huda Khan Asghar. Energy efficiency improvement in electron beam purification of silicon by using graphite lining, *Energy*, Volume **185**, pp. 102-110, (2019), https://doi.org/10.1016/j.energy.2019.07.038.
6. Wen Yan, Guiyuan Wu, Sanbao Ma, Stefan Schafföner, Yajie Dai, Zhe Chen, Jiangtao Qi, Nan Li. Energy efficient lightweight periclase-magnesium alumina spinel castables containing porous aggregates for the working lining of steel ladles. J. of the European Ceramic Society. Volume **38**, Issue 12. pp. 4276-4282, (2018), https://doi.org/10.1016/j.jeurceramsoc.2018.05.002.
7. D.V. Mendelev, Application of energy-efficient lining designs to reduce fuel consumption in industrial furnaces / D. V. Mendelev, I. A. Trusova, P. E. Ratnikov // *Casting and metallurgy: scientific and production journal*, № **2** (65), pp. 108 – 112, (2012).
8. Yichong Li, Huizhong Zhao, Yang Yang, Zecheng Feng, Han Zhang, Jun Yu, Yanli Liu, Li Feng. The restructuring-sintering mechanism of calcium alumino-titanate in tundish permanent lining castables. *Ceramics International*. Volume **46**, Issue 18, Part A. pp. 29282-29289, (2020). https://doi.org/10.1016/j.ceramint.2020.08.102.
9. K. K. Strelov, I. D. Kascheev, D.S. Rutman, I.I. Nemets, L.B. Romanovsky, Refractory protection // *Refractories*, №**8**. pp. 48-52 (1983).
10. I. Istadi, Y. Bindar Improved cooler design of electric arc furnace refractory in mining industry using thermal analysis modeling and simulation. *Appl. Thermal Engineering* **73** (1) pp. 1129-1140, (2014), https://doi.org/10.1016/j.applthermaleng.2014.08.070.
11. Huining Zhang, Peiling Zhou, Fei Yuan. Effects of ladle lid or online preheating on heat preservation of ladle linings and temperature drop of molten steel. *Energy*. Vol. **214**. (2021), https://doi.org/10.1016/j.energy.2020.118896.
12. A. S. Afanasiev, A. V. Borodulin, I. Sultanguzin, S. N. Yarunin, & A. Yashin Energy analysis of thermal operation of coke-oven batteries. *Solid Fuel Chemistry*. **37**(1):62 – 69, (2003).
13. M.Emre Ertem, Abdulkadir Özdabak, Energy balance application for Erdemir Coke Plant with thermal camera measurements, *Applied Thermal Engineering*, Vol. **25**(2–3), pp. 423-433. (2005).
14. K. Pourabdollah, MS Zakaria, SMM Najafizadeh. Optimization of operating conditions in desulfurization of petroleum coke using induction heating. Asia-Pac *J Chem Eng*., Vol. 15, (1) (2020); https://doi.org/10.1002/apj.2398.
15. Bin Zheng, Yongqi Liu, Lichen Zou, Ruiyang Li, "Heat Transfer Characteristics of Calcined Petroleum Coke in Waste Heat Recovery Process", *Mathematical Problems in Engineering*, vol. **2016**, Article ID 2649383, (2016). https://doi.org/10.1155/2016/2649383.
16. M. Bernd. et al. “Synthesis of carbon nanostructures by the pyrolysis of wood sawdust in a tubular reactor, *Journal of materials research and technology* **6** pp.171-177 (2017).
17. M. M. Akhmetov. Petroleum coke calcination processes — present and future. *Chem Technol Fuels Oils* **22**, pp. 321–333 (1986). https://doi.org/10.1007/BF00730517.
18. I. I. Lapaev, V. V. Sorokin, S. E. Goloskin et al. Lining of the Rotary Kilns for Petroleum Coke Calcination. *Refract Ind Ceram* **60** (1–5) (2019). https://doi.org/10.1007/s11148-019-00299-w.

19. Fabrice Patisson, Etienne Lebas, François Hanrot, Denis Ablitzer, Jean-Leon Houzelot. Coal pyrolysisin a rotary kiln: Part II. Overall model of the furnace. *Metallurgical and Materials Transactions* B,Springer Verlag, **2**,31, pp. 391-402 (2000),. https://doi: 10.1007/s11663-000-0057-4.
20. E. Brochen, J. Pötschke and C. G. Aneziris, Improved Thermal Stress Resistance Parameters Considering Temperature Gradients for Bricks in Refractory Linings. *Int. J. Appl. Ceram. Technol.*, **11**: pp. 371-383, (2014) https://doi.org/10.1111/ijac.12022.
21. A. K. Akishev, S. M. Fomenko & S. Tolendiuly. Effect of Refractory Thermal Stresses and Parameters on Development of the Internal Temperature Field. *Refract Ind Ceram* **60**, pp. 561–565 (2020). https://doi.org/10.1007/s11148-020-00407-1.
22. V. O. Sinelnikov, D. Kalisz & R. D. Kuzemko. Study of the Phase and Mineralogical Properties of Converter Slag during Splashing to Improve Lining Resistance. *Refract Ind Ceram* **59**, pp. 403–409 (2018). https://doi.org/10.1007/s11148-018-0244-y.
23. Y.V. Sharikov. Control system of the roasting process in tubular rotary kilns using thermal imaging scanning / Y.V. Sharikov, T.O. Koyranen. *Notes of the Mining Institute*. Vol.221, pp.681-687 (2016). https://doi10.18454/ PMI.2016.5.681.
24. A. S. Nikiforov, E. V. Prikhod'ko. Thermal Stresses Generated in the Lining of a Steel Ladle. *Refract Ind Ceram* **46**, pp. 360–363 (2005). https://doi.org/10.1007/s11148-006-0012-2.
25. Bowen Luo, Gongfa Li, Jianyi Kong, Guozhang Jiang, Ying Sun, Ze Liu, Wenjun Chang, Honghai Liu.. Simulation Analysis of Temperature Field and Its Influence Factors of the New Structure Ladle. *Applied Mathematics & Information Sciences*. **11**. pp. 589-599 (2017), DOI: 10.18576/amis/110231.
26. Nikiforov A. S., Prikhod’ko E. V., Kinzhibekova A.K., Kucher E.O., Niconov G.N. Method for determination of thermal state of fettling of heating unit. KZ26932-A4, 15 May (2013), G01K-013/00.
27. Nikiforov A. S., Prikhod’ko E. V., Kinzhibekova A. K., Karmanov A. E. Investigation of the Dependence of Refractory Thermal Conductivity on Impregnation with a Corrosive Medium. Refractories and Industrial Ceramics, Vol. 60, No. 5. Pp. 463- 467. January, 2020; doi:10.1007/s11148-020-00386-3.
28. Prikhodko E. V. Development of a method for monitoring the process of heating the lining of high-temperature units, *J. Sib. Fed. Univ. Eng. & Technol.*, **13**(4), pp. 462-472, (2020), DOI: 10.17516/1999-494X-0233.