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Trotsenko L.M., *Candidate of Technical Sciences, ORCID: 0000-0002-1773-0427,* ***Aleksyeyenko V.V.,*** *Candidate of Technical Sciences, ORCID: 0000-0002-9060-4902,* ***Pikashov V.S.,*** *Candidate of Technical Sciences, ORCID: 0009-0002-1602-7278*

The Gas Institute of the National Academy of Sciences of Ukraine
39, Degtyarivska Str., 03113 Kyiv, Ukraine, e-mail: t-ln@ukr.net

Comparative Analysis of Energy Efficiency of Thermal Operation of Rotary Kilns with Different Heating Systems

Abstract. Analysis of the design features of known heating systems for large rotary kilns and modern methods of influencing the formation of the flame and the distribution of the temperature profile is presented. It has been established that most of the known methods of forming the flame and temperature profile of the working space of rotary kilns are based on methods of influencing air flows, in particular secondary air, the share of which in the total volume of combustion air is 70–100 %. On the basis of previous studies and observations, it is proposed to form a flame using additional sideways gas jets from the burner. Examples of modernization of heating systems of existing industrial rotary kilns for firing various materials, including ferronickel ore, fireclay, and lime, are presented. After installing burners with controlled flame parameters and changing the design of the combustion air supply system in the working space of the kilns, an optimal temperature distribution along their length was obtained. It was determined that the required temperature at about half the length of the kilns is almost constant, without significant fluctuations, differing at the beginning and end of the firing zone by 30–70 °C. The decrease in the temperature of the exhaust gases from the kilns after the modernization of the heating systems indicates an intensification of heat exchange in the workspace, which leads to a decrease in specific fuel consumption by 7–15 %, as well as an improvement in the quality of the final material. A comparative analysis of the thermal efficiency of operating rotary kilns depending on the design features of the heating system is presented. *Bibl. 24, Fig. 4.*

Keywords: rotary kilns, shape and parameters of the flame, temperature profile, gas and air flows, heat transfer, thermal efficiency.

Introduction

The high cost of fossil fuels, in particular natural gas, and the unacceptable dependence on individual countries for their supplies from the point of view of energy security, makes the international community look for different ways to save such fuels. This is usually achieved by increasing the efficiency of their use or replacing them with alternative fuels (biogas, liquid fuels, waste pyrolysis and gasification products, etc.) and waste combustible gases (coke and blast furnace gases, ferro- and ore-thermal gases, oil refining gases). For rotary kilns with high heat capacity (> 20.0 MW), the replacement of fossil fuels is particularly relevant and makes a significant impact on their savings.

In [1], it was proposed to partially replace natural gas with synthetic gas obtained in the process of cooling the material and its combustion in the working space with the addition of air directly into the high-temperature zone of the kiln for calcining carbon-containing raw materials (coke). It is shown that this minimizes fossil fuel consumption and reduces the energy intensity of the process.

In [2], based on numerical studies, it was proved that the thermal efficiency of a rotary kiln can be increased by introducing an insulating material with a lower thermal conductivity into the lining.

In recent decades, the world has developed a wide range of experience in the development and use of multi-fuel (multi-channel) burners for rotary kilns for various purposes. Such burners allow burning different fuels simultaneously or separately, providing full or partial replacement of fossil fuels [3–9].

For example, Dynamis [10] claims that solid fuels can be more efficient than gas and oil. According to this company, when replacing natural gas with coal, the productivity of kilns increases by 2–3 percent. This is mainly due to the higher emissivity of the coal flame, as radiation is the main mechanism of heat transfer inside a rotary kiln [10]. The emissivity of coal flames is approximately 0.85, while the emissivity of oil and gas flames is approximately 0.5 and 0.3, respectively. It is also known that a large contribution to the flame radiation is caused by particles of coal, petroleum coke and fly ash suspended in the stream, as well as from soot generated during the combustion process.

However, there are also negative aspects of using alternative fuels in industrial kilns. Some alternative fuels can introduce substances into the burners and the kiln that result in overgrowth of nozzles, pipelines, gas valves, and draft devices, thus causing damage and deterioration of the operation of individual kiln components. In [11], attention is also drawn to the impact of alternative fuels on the formation of the temperature profile of rotary kilns. For example, some fuels are characterized by an extended flame, which changes the quality of heat treatment, in particular the mineralogy and reactivity of clinker or lime by reducing heat transfer in the firing zone. Alternative fuels also introduce more air, moisture and ash into the kiln, which reduces the thermal efficiency and capacity of the kiln.

Therefore, regardless of the fuel used, intensification of heat transfer in the working space is one of the most important areas for optimizing kiln efficiency.

Problem statement and literature review

It is known that one of the conditions for the stable and efficient operation of thermal kilns is the control of their temperature regime, in particular, ensuring the required temperature distribution for different technological conditions.

In [3], using CFD modeling, it was shown that the highest temperature of flue gases formed as a result of fuel combustion in a cement kiln without special measures to regulate the burning zone or length of the flame is formed near the burner outlet, decreasing with increasing distance from it. It has been shown that the formation of an excessively long flame leads to deterioration of heat transfer in the high-temperature firing zone, and an increase in the temperature of the exhaust gases, which reduces the efficiency of the furnace. A short flame for rotary kilns generates excessive temperatures in the combustion zone, which causes overburning of the material surface and a decrease in its quality, and there is a risk of exceeding the fire resistance of the lining [4].

When a flame is formed that is too long, heat transfer in the high-temperature firing zone deteriorates, the temperature of the exhaust gases increases, which reduces the efficiency of the kiln. Therefore, the proper formation of the flame parameters in the rotary kiln plays an important role.

In [12], heat transfer along a rotary kiln was modeled. It is shown that convective heat transfer to the material is influential at low temperatures, and with an increase in temperature above 950 °C (in the firing or calcining zone), thermal radiation is dominant. Therefore, the proper formation of the temperature profile and flame parameters in the kiln plays an important role.

In practice, the optimal heating conditions for specific technological conditions, material properties, and the thermal operation of the kiln are set using different designs of kiln heating systems.

For example, [4] shows that the quality of lime depends on the characteristics of the flame: soft, medium, or hard. That is, one of the main parameters that affects the reactivity of lime and residual carbonate is the shape, stability of the flame and the corresponding temperature profile of the kiln.

The main factors affecting the regulation and efficiency of the burner are indicated in [5]. These are the impulse of individual fuel and air jets, turbulence index, primary air coefficient, and vortex number. It is shown that the control by involving secondary air in the fuel flow with the help of primary air in D-Flame burners influences the formation of recirculation zones and an increase in the level of turbulence, which determines the intensity of the processes of mixing fuel with an oxidizer.

This fact is also confirmed in [13]. It is shown that the parameters of the flame from the burner depend on the structures of secondary and tertiary air flows, given that up to 100 % of the combustion air comes from these sources, and the impulse of these large air flows dominates the combustion area. It is noted in [14] that as a result of the uneven flow of secondary air into the rotary kiln, the flow of which enters the working space from below and moves upward along a curved path past the burner, the flame also tends to rise upward to the upper part of the working space (in the opposite direction from the material to be heat treated). This is also evidence of the influence of the secondary air flow on flame formation, which is usually highly dependent on the momentum and direction of the secondary air.

Aerodynamic modeling of the rotary kiln using Ansys Fluent and experimental indirect data of the kiln temperature profile on the outside of the rotary kiln steel shell [15] also showed a correlation between the hot secondary air flow and the temperature distribution along the kiln length. It is pointed out that the recirculation zone is of primary importance when combustion is taken into account, since the reverse flow improves the stability of the flame and affects combustion efficiency. The control of the secondary air flow has a significant impact on the temperature distribution, especially in the combustion zone.

In [6, 10], the effect of various parameters on the energy consumption and efficiency of rotary kilns was studied using CFD modeling. By simulating the combustion of gas and solid fuels and radiation heat transfer using Ansys Fluent, the temperature, velocity, and trajectory profiles of gas flows and coal particles inside the kiln, including the near burner area, were determined. The studies were conducted for various heating system parameters of a full-scale cement kiln. The results showed that the calculated temperature in the clinker layer area can vary by up to 200 °C depending on the design of the heating system. In the cases with a reduced air inlet area and a centralized tertiary air inlet, the velocity vectors had slightly deviated profiles, which in turn affected the temperature and particle trajectory profiles. The case where the burner is inserted 0.5 m into the kiln working space improves the calculated velocity, temperature, and particle trajectories, as the results show very homogeneous and symmetrically distributed profiles for both the continuous and dispersed phases. This system provides more secondary air injection into the fuel injection area.

In [7], the aerodynamics and combustion of pulverized coal fuel were studied using CFD modeling of a full-scale rotary cement kiln with a multichannel swirl burner. A heat transfer model with a zonal heat transfer coefficient is also presented, which takes into account the heat transfer from the flue gases to the reacting mass and the environment. Four different cases where the burner vane angles were varied from 22.5° to 45° were studied and their effect on the flame profile, temperature distribution, and concentration of substances. The results show that reducing the vane angle from 30° to 22.5° leads to a radial reduction of the zone with a higher temperature. With higher vane angles of 37.5° and 45°, the flame length decreases, and the zone with a higher temperature extends radially to the refractory wall. It was also found that although the change in vane angles has a certain effect on the flame profile, it does not have a significant impact on the overall temperature distribution inside the rotary kiln.

In [16], a two-dimensional axisymmetric model was developed using Ansys Fluent to understand the main operational and geometric parameters of rotary kilns that affect flame behavior, including aerodynamics and heat transfer. In this study, three fuels were used: methane (CH_4), carbon monoxide (CO), and biogas (50 % CH_4 and 50 % CO_2). The correlations of the limited jet plume length depending on the operational and geometric parameters of the rotary kiln were developed and presented. It was found that such characteristics of the flame as length, shape, and intensity are crucial for improving the efficiency of the kiln. In addition, they have a strong influence on the heat transfer rate, and thus on fuel consumption, product quality, total reduced sulfur emissions, nitrogen oxide emissions, and refractory life.

The well-known flame control system for cement rotary kilns based on the Pillard Rotaflame multi-channel burner ensures repeatable flame formation, limits operational risks associated with incorrect temperature settings in the kiln, and provides optimal flame impulse due to the reduced pressure drop in the burner and the patented nozzle design that allows for rapid suction of secondary air [4]. The Pillard Rotaflame burner has adjustable tip cross-sections for axial, radial air and natural gas supply, and can accommodate tuyeres for solid and liquid fuels, and also nozzles for gaseous fuels. It has been shown that gas of a certain pressure can generate sufficient momentum to mix with hot secondary air, and the low O_2 content in the flame core helps to reduce the temperature in the combustion zone and reduces harmful emissions into the environment.

Based on the review of the above studies, it is possible to conclude that it is possible to control the flame parameters and temperature distribution in the kiln using combustion air flows. However, information on the length, shape, and direction of the flame, and their impact on the final thermal performance of operating rotary kilns is not fully understood. There is no data on the distribution of fuel in the burners and its impact on the formation of the flame and temperature profile. In addition, the above publications do not contain data on the influence of the flame shape and temperature profile of the working space on the quality of the finished material after heat treatment in industrial kilns.

It is known that for the efficient operation of a flame in a rotary kiln, it is necessary that the location of its maximum heat transfer coincides with the location of the required maximum heat consumption.

Studies also show that the most intense heating of the material surface is achieved when the flame and the flow of combustion products are directed directly at it [17]. However, such heating is justified only in cases where the quality of the material to be heated or burned is not limited by the maximum temperature on its surface, or when the layer of material to be heated evenly is thermally thin.

Therefore, for the efficient operation of the rotary kiln and the high quality of the material it produces, the following conditions must be created in the working space:

— to ensure a temperature distribution that meets the technological requirements for heating the material. In particular, in the zone of mineralogical transformations of the material (firing zone), to ensure the required temperature along all or most of its length without significant exceeding the level of required temperatures;

— to ensure efficient heat exchange with minimization of the temperature of the exhaust gases;

— to reduce the uniformity of heating of the material layer along its thickness.

Results and discussion

The main difference of rotary kilns derives from their design and material movement. The inner surface of the lining of the rotating part of the rotary kiln is in alternating contact with the heating gases and the material to be heated. In other words, in rotary kilns, a complex heat exchange takes place: from the flame and combustion products by radiation and convection to the free surface of the material and to the internal free surface of the lining, which re-radiates heat to the material through transparent or translucent combustion products. Heat is additionally transferred to the material by contact of the internal layers with the lining, which is heated by the flame and then releases heat to the material upon contact with it at each kiln turnover. In other words, complex heat transfer (contact heat transfer, convection and radiation) takes place.

The heating rate of the material in such kilns depends on the optimal temperature distribution along the length of the kiln. And the quality of heat treatment determines the degree of asymmetry of heat supply to the free surface and internal layers of the material.

Many rotary kilns in Ukraine operate according to the classical scheme, when fuel is supplied to the kiln by one or two burners installed at the end of the retractable head (Fig. 1). When two burners

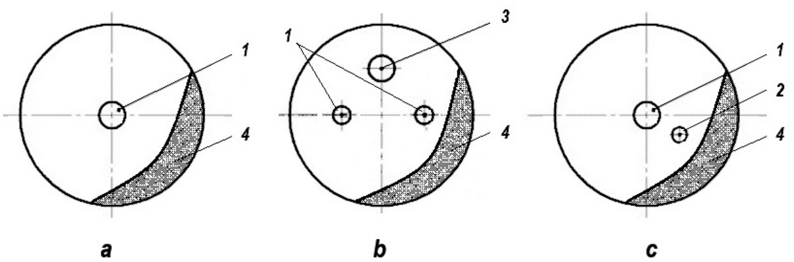


Figure 1. Scheme of burner installation on the front side of the retractable kiln head before modernization: 1 — burners; 2 — auxiliary burner near the surface of the material; 3 — air pipe; 4 — material to be heated.

are used, both can be installed at an equidistant distance from the kiln axis, which means that there is an evenly distributed heating mode in accordance with the classification in [18]. In another case, one burner is installed along the axis of the furnace cylinder, and an auxiliary side burner is installed near the surface of the bulk material to create a flame that radiates along the surface of the material.

Combustion air can be supplied in three ways, conditionally divided into 3 groups.

1. All the air required for fuel combustion in the cold state is forced into the burner devices. This method of air input is used in kilns where the fired material is directly fed for further processing, for example, in ferronickel ore firing kilns before it is fed to smelting kilns. In terms of energy saving, this organization of air input for combustion in rotary kilns is the least efficient.

2. All the combustion air heated in the cooler of the finished material is supplied to the kiln by a smoke exhauster behind the kiln and a fan in front of the cooler. In this case, the thermal efficiency of the kiln is somewhat higher than in the previous case. However, the supply of air in an unorganized flow into the kiln working space does not create optimal conditions for its mixing with the fuel, and therefore the combustion process is uncontrolled, the distribution of the kiln into technological zones is disturbed, which reduces the thermal efficiency of the kiln.

3. Part of the air, called primary air, is supplied directly to the burner for the initial formation of the flame. The rest of the secondary air, heated in the material cooler, is fed directly into the workspace by the draft behind the kiln and the pressure of the fan in front of the cooler and is disorganized. The heating air temperature can range from 400 °C to 800 °C.

The most perspective and effective direction is a reasonable combination of two trends in the supply of air for combustion in kilns: its heating and organized supply, which provide the best conditions for the formation of the flame and the temperature field in the working space.

This paper presents a comparative analysis of the thermal performance of rotary kilns for firing oxidized nickel ores, kaolin to fireclay, and limestone to lime, whose heating systems are schematically shown in Figure 1.

In the rotary kiln for firing oxidized nickel ores, a fuel oil burner was installed along the kiln axis (Fig. 1, a), which was supplied with cold air in the amount necessary for combustion. Single pipe burners were installed in the retractable head of the chamotte rotary kiln in accordance with the scheme in Fig. 1, b. Primary cold air in the amount of 25–30 % of the total required was supplied to the air pipe located above the burners, secondary hot air from a drum-type cooler was supplied from below to the tumbling head and then to the kiln. In lime kilns (Fig. 1, c), all the air required for combustion was supplied hot to the kiln from the bottom of the shaft-type cooler.

Such heating systems for the kiln working space create conditions for non-uniform gas and air velocity flows across the cylinder, which means that the flame burning zone (high temperature zone) does not always meet the technological requirements for the temperature profile.

Thus, in the case of equidistant location of the burners and the supply of primary air above the burners through the air pipe, and secondary air from below through the neck of the cooler, an irregular temperature distribution in the working space is formed in most parts of the kiln. The CFD modeling of the velocity and concentration characteristics of gas and air flows [19] showed that the beginning of fuel mixing with air occurs at some distance from the burner and continues along the parallel movement of gases and air along the kiln cylinder. This results in combustion stretching and flame shifting to the discharge end of the flow. In addition, the flame develops in the upper part of the working space opposite to the material. That is, the location of the flame is remote from the surface of the material and separated from it by gases with a lower temperature, which, according to [20], reduces the intensity of heat transfer.

In cases where the auxiliary burner is located near the surface of the charge, significant temperature gradients occur in the material layer with insufficient heating of its inner layers. This approach does not ensure sufficient uniformity of material heating. All of the above reduces the productivity of the kilns and the quality of the final product.

The Gas Institute of the National Academy of Sciences of Ukraine has developed three types of burners with adjustable flame parameters for 3 types of combustion air supply organization, which operate on natural gas:

– PG-35 for supplying 100 % cold air to the burner [21];

– PG-35M for supplying a part of the combus-

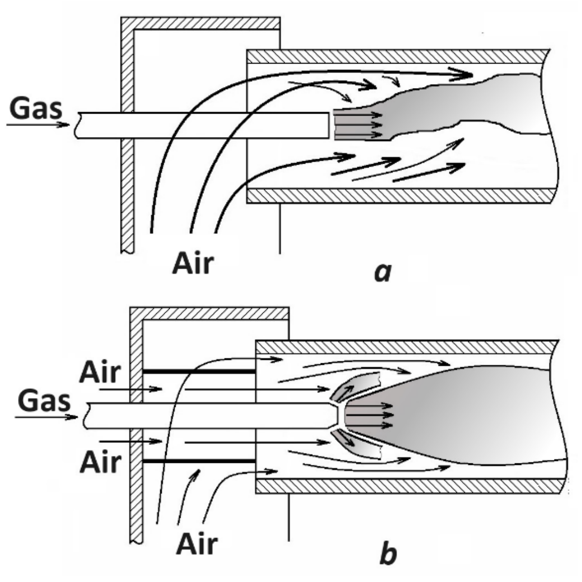


Figure 2. Scheme of flame formation in the absence (*a*) and presence (*b*) of auxiliary side air jets.

tion air to the burner from the total combustion air;

— GURF-30 without air supply to the burner for operation in kilns with all combustion air supplied through the cooler of the finished material directly to the kiln.

The design of these burners is different in that they provide for the adjustment of the flame parameters due to the variable flow of natural gas through the axial and lateral gas nozzles evenly spaced around the perimeter of the burner. With an increase in fuel consumption through the lateral nozzles, the flame expands, approaching the surfaces of the material and lining. This, according to [20], creates conditions for the integration of heat transfer in the firing zone.

Previous observations, studies, and analysis of the conditions of flame formation, it was determined that the side gas jets directed at an angle of 45–90° to the burner axis partially screen the air flow to the central flow of flushing gas from the axial nozzle (Fig. 2). Therefore, at first, part of the air is used to mix with the gas from the side nozzles and combust it, and then at a certain distance from the burner's outlet axial nozzle, the rest of the air gradually mixes with the axial gas jet. Thus, a wide, extended diffusion flame is formed, and its combustion occurs almost along the entire length of the firing zone. This shape of the flame and its combustion conditions result in intensive heat transfer over the maximum length.

Description of rotary kiln heating systems after modernization

During the modernization of the kilns described in this article, the heating system was changed with the installation of appropriate burners with adjustable flame parameters along the kiln axis. When replacing fuel oil with natural gas, a PG-35 burner was installed in the nickel ore firing kiln [22]; a PG-35M burner was installed in the chamotte firing kiln; and a GURF-30 burner was installed in the lime firing kiln.

The distribution of combustion air into primary and secondary air in the chamotte kiln remained without change. The primary cold air was supplied to the PG-35M burner at 25–30 %, and the secondary hot air at 70–75 % of the required amount. In the lime kilns, a GURF-30 burner was used, which is fed only with fuel gas.

In the retractable head an air collector in the form of a cylinder with a length not less than the length of the retractable head (Fig. 3, *a*) and with a diameter that covers the air supply holes (Fig. 3, *b*) was also proposed and installed in the lime kiln. The cylindrical air collector restricts the air jets, preventing them from rising to the top of the kiln retractable head and ensures air movement around the fuel flow [23].

Thus, the formation of an organized and evenly distributed air flow in the working space of the cylinder in the combustion zone is ensured. The direction of the flow of air heated in the cooler around the gas flow supplied through the burner contributes to their uniform mixing and controlled

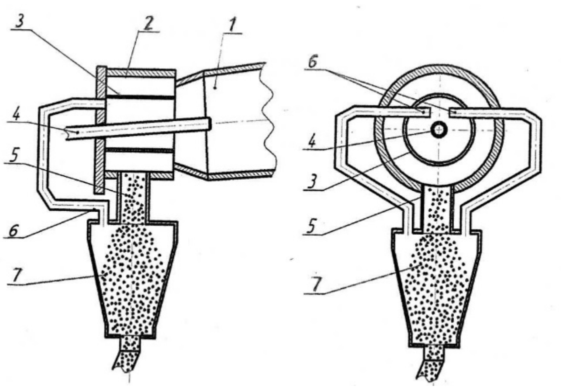
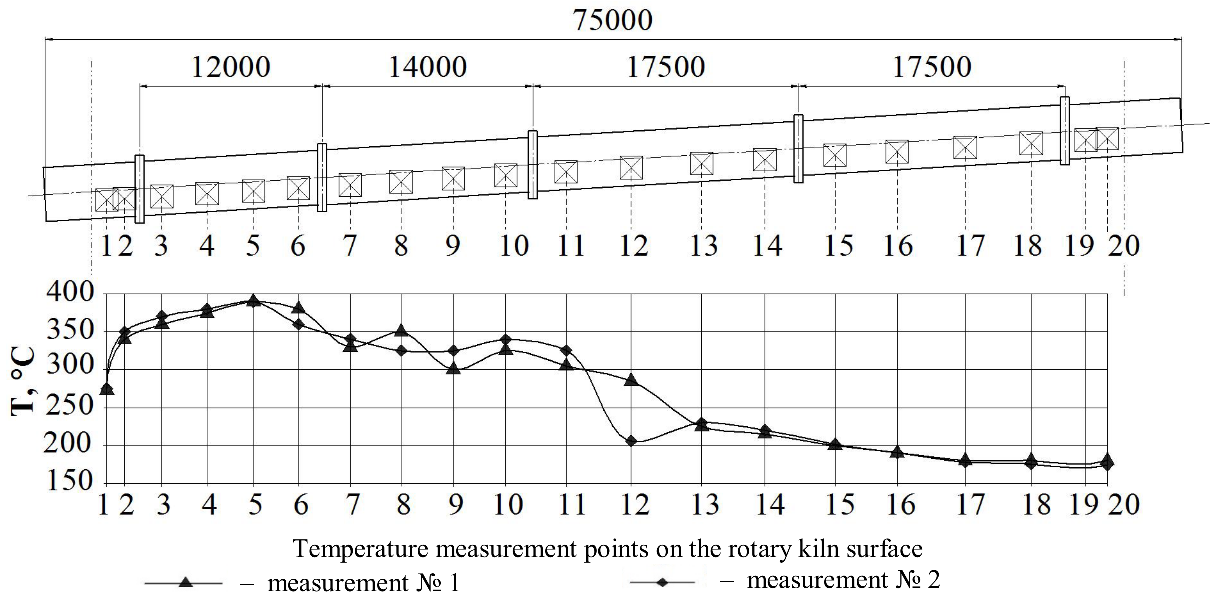
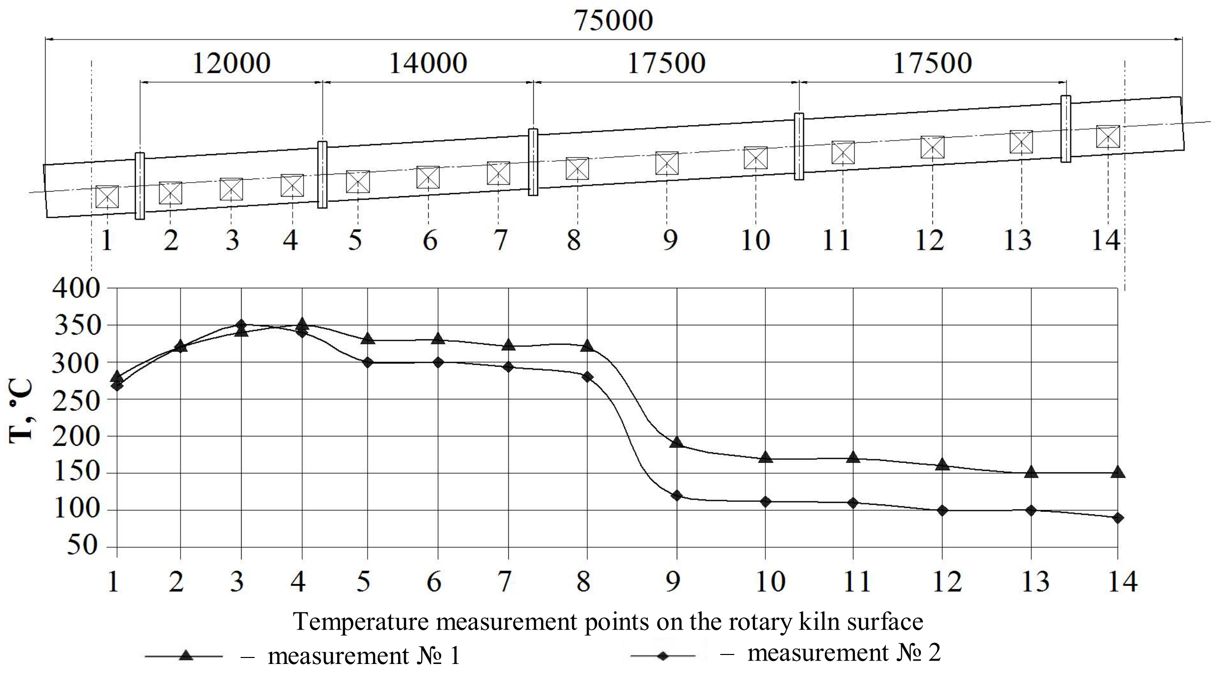


Figure 3. The design of the modernized discharge end of a rotary kiln with an air collector: 1 — rotary part of kiln; 2 — retractable (discharging) kiln head; 3 — air collector; 4 — burner; 5 — cooler neck; 6 — air pipes; 7 — cooler.



a



b

Figure 4. Temperature of the steel shell of the rotating part of the kiln before (*a*) and after (*b*) reconstruction.

combustion. This makes it possible to increase the level of rigidity and stability of the flame, increase the intensity of heat transfer in the kiln, improve the quality of heat treatment of the material and fuel efficiency [24].

An example of the temperature distribution on the outside of the steel shell of an existing lime kiln at Azovstal before and after the heating system modernization is shown in Fig. 4.

The temperatures shown on the graph should be understood as averaged over the perimeter of the steel shell in the section marked with a point.

The figure shows that after the modernization of the rotary kiln heating system, the temperature distribution over approximately half the length of the kiln is stable, has no peaks, differing at the beginning and end of the firing zone by 30–70°. This is confirmed by the temperature profile on the steel shell of the rotary kiln cylinder in the firing zone. The decrease in the temperature at the kiln outlet, which decreased from 170–180 °C to 100–150 °C after the heating system modernization, indicates an increase in the heat transfer intensity.

Below are the main parameters of the thermal operation of the kilns mentioned in the article.

Table 1. Comparative analysis of the thermal performance of rotary kilns

Indicators	Rotary kiln for the firing of nickel ores		Rotary kiln for firing kaolin into fireclay		Rotary kiln for limestone calcination into lime	
	before modernization	after modernization	before modernization	after modernization	before modernization	after modernization
The size of the cylinder, D × L, m	3.6 × 80		3.6 × 75		3.6 × 75	
Heating system	Fig.1, *a*	burner with adjustable flame parameters PG-35	Fig.1, *b*	burner with adjustable flame parameters PG-35M	Fig. 1, *c*	burner with adjustable flame parameters GURF-30; air collector
Type of fuel	fuel oil	natural gas	natural gas	natural gas	natural gas	natural gas
Natural gas consumption, m^3/h	40 МВт*	3500	3100	2200	3242	3238
Capacity, tons/hour	30	35	19–23	18–23	15.8	16.8
Primary air consumption, %	100 (cold)	100 (cold)	25–30 (cold)	25–30 (cold)	0	0
Secondary air consumption, %	0	0	70-75	70-75	100	100
Secondary air temperature, °C	0	0	500–700	500–700	600–700	600–700
Excess air coefficient	1.2–1.4	1.05–1.18	1.1–1.3	1.05–1.1	1.2–1.3	1.15–1.21
Temperature in the firing zone, °C	1000–1100	1000–1100	1450–1500	1450–1500	1250	1250
Quality of firing	–	–	2 class	1 class	96.94 %	98.0 %
Temperature before the filters, °C	400–500	100–200	250–280	180–190	170–180	90–150
Specific fuel consumption for obtaining the final material, kg of fuel equivalent/t	109.11	87.2	155.9–188.8	111.9–141.8	257.4	212.6–242.0

Notes: * — heat output when the kiln operates on fuel oil.

Conclusions

The analysis of the thermal operation of rotary kilns with different heating systems showed that the design features of heating systems, which improve the conditions for mixing fuel with air and regulate the shape and direction of the flame, contribute to a significant increase in the energy efficiency of the kilns.

Controlling the air and fuel jets in the kiln and burner allows for an optimal temperature profile in the working space.

On the example of the rotary kilns presented in this article, it is shown that the control of the flame parameters in them allowed us to obtain the following results:

— ensuring a uniform temperature distribution along the entire length of the high-temperature zone, which makes it possible to improve the quality of heat treatment of the material and the final product;

— reducing the temperature on the outer surface of the rotating cylinder at its loading end, which indicates the intensification of heat exchange in the working space;

— ensuring stable operation of the kilns with a minimum air consumption coefficient;

— due to the wide flare, providing intensified heating of the lining, which plays an important role in heating the material.

It has been shown that rotary kilns for various purposes with modern heating systems based on burners with adjustable flame parameters can save fuel from 5 % to 30 %, increase the productivity of kilns while maintaining or improving the quality of the final product.

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Троценко Л.М., *канд. техн. наук, ORCID: 0000-0002-1773-0427,*
Алексеєнко В.А., *канд. техн. наук, ORCID: 0000-0002-9060-4902,*
Пікашов В.С., *канд. техн. наук, ORCID: 0009-0002-1602-7278*

Інститут газу Національної академії наук України
вул. Дегтярівська, 39, 03113 Київ, Україна, e-mail: t-ln@ukr.net

Порівняльний аналіз енергоефективності теплової роботи обертових печей з різними системами опалення

Анотація. Наведено аналіз конструктивних особливостей відомих систем опалення великих обертових печей випалу та сучасних способів впливу на формування факела та розподілу температурного профілю. Встановлено, що більшість відомих способів формування факела та температурного профілю робочого простору паливних обертових печей засновано на методах впливу на потоки повітря, зокрема вторинного, доля якого у загальному об’ємі повітря на горіння складає 70–100 %. На основі попередніх досліджень та спостережень запропоновано формування факела за допомогою додаткових бокових струменів газу з пальника. Наведено приклади модернізації систем опалення діючих промислових обертових печей для випалу різних матеріалів, зокрема феронікелевої руди, шамоту та вапна. Після встановлення пальників з регульованими параметрами факела та зміни конструкції системи подачі повітря на горіння в робочому просторі печей отримано оптимальний розподіл температури по їх довжині. Встановлено, що необхідна температура приблизно на половині довжини печей є майже незмінною, без значних коливань, відрізняючися на початку та наприкінці зони випалу на 30–70 °С. Зниження температури відхідних газів з печей після модернізації систем опалення свідчить про інтенсифікацію теплообміну в робочому просторі, що призводить до зменшення питомих витрат палива на 7–15 %, а також покращання якості кінцевого матеріалу. Наведено порівняльний аналіз теплової ефективності роботи діючих обертових печей у залежності від конструктивних особливостей системи опалення. *Бібл. 24, рис. 4.*

Ключові слова: обертові печі, форма та параметри факелу, профіль температур, газові та повітряні струмені, теплообмін, ефективність теплової роботи

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