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IMPROVEMENT OF HEAT UTILIZATION SYSTEMS WITH THERMAL PROCESS STABILIZATION IN ROTARY KILNS

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Abstract. This article is devoted to improving heat utilization systems for industrial and municipal heat supply. It outlines methods for enhancing the cooling systems of kilns used in the firing of construction materials, identifies ways to stabilize the thermal regime, and establishes the conditions for developing functional layouts for furnace units. Rotary kilns, operating under varying environmental influences such as air temperature, wind speed, solar radiation, and atmospheric precipitation, lose up to 30% of their heat through the lateral surface into the surrounding environment. These external factors negatively affect the thermal condition of the furnace unit, leading to overheating during warm periods and overcooling in cold seasons, which in turn decreases the durability of the lining and the quality of the produced materials.

Typically, natural cooling of the kiln side surface is assumed in order to maintain the necessary internal surface temperature and extend the lining's lifespan. However, this is an uncontrolled process with the aforementioned disadvantages.

One approach to increasing the efficiency of fuel combustion heat utilization is the implementation of a regulated cooling system for rotary kilns. One possible solution is a recirculating channel design, which relies on the repeated use of the heat carrier flow. The share of recirculated flow increases as outdoor temperature decreases. Under summer design conditions, the system operates as a direct-flow type, delivering the entire stream to end users. In winter conditions, air is supplied from the bypass line.

Based on these considerations, formulas are derived for determining the main parameters of the stabilizing cooling system for rotary kilns, intended for residential and municipal heat supply applications.

Keywords: rotary kiln, heat recovery, industrial heat supply, air cooling, thermal regime stabilization.

Introduction. In the construction materials industry, improving the efficiency of fuel and energy resource use is a critical issue, especially for the production of energy-intensive products such as expanded clay, cement, lime, reinforced concrete structures and ceramic wall materials. These product types account for more than 50% of all fuel and energy resources consumed annually by the construction sector [1, 2].

Rotary kilns, operating under variable external conditions – including fluctuations in air temperature, wind speed, solar radiation, and precipitation – lose up to 30% of the utilized heat through their side surfaces into the environment. These impacts result in overheating of the kiln during warm seasons and excessive cooling during cold periods, ultimately reducing the durability of the lining and the quality of the final product.

To maintain the required temperature on the inner surface of the kiln and extend the service life of the lining, natural cooling of the unit's lateral surface is used. However, this is an uncontrolled process with certain drawbacks.

A radical solution for meeting thermal process requirements and improving the efficiency of fuel combustion energy recovery is the implementation of controlled cooling of the rotary kiln.

Review of Recent Research and Publications. In addition to the main publications [3-10], there are also studies [11-16] that propose new technical concepts aimed at improving the efficiency of heat utilization from the primary fuel during the processes of extraction, transformation, and utilization of waste heat from kiln surfaces. An analysis of existing technical solutions for applying recovered heat in industrial heat supply systems indicates the need for improving functional schemes that ensure a specified cooling level for furnace units.

Problem Statement. Meeting technological requirements and increasing the efficiency of heat utilization from fuel combustion can be achieved by organizing regulated cooling of rotary kilns. The development of heat supply systems based on the energy obtained from controlled kiln cooling highlights the need to refine the functional schemes that provide the required level of kiln unit cooling, while also enabling the use of recovered heat for industrial heat supply.

Materials and Methods. Rotary kilns are complex units where all thermal processes are implemented – from controlling the amount raw materials of input to obtaining the final product of the desired quality.

The general methodology for achieving the set objectives involves developing approaches and solutions from the perspective of treating the kiln as a powerful source of secondary heat. Based on this, conditions should be established for the rational extraction and utilization of heat from the outer surface of the unit.

The methodology is based on the energy balance between the justified volume of technological heat consumption and heat losses due to various non-productive expenditures. It also incorporates analysis of known methods for reducing heat consumption, the capabilities of consumer heat consumption systems, the impact of harmful environmental factors, and the recent significant increase in the cost of fuel.

The solution involves the use of mathematical and experimental modeling of thermal and aerodynamic processes. Experimental research is also required in laboratory settings with validation of the obtained results under industrial conditions.

Research Results. Stabilizing the thermal regime of a kiln using the proposed enclosure is based on extracting a specific amount of heat during the operational period, regardless of changes in the outdoor temperature. This ensures a relatively consistent thermal state of the kiln unit throughout its operation [8-10].

One of the simplest possible schematic solutions for implementing the proposed kiln arrangement is the use of direct-flow heat extraction systems from the surface of the rotary kiln (see Fig. 1, options *a* and *b*).

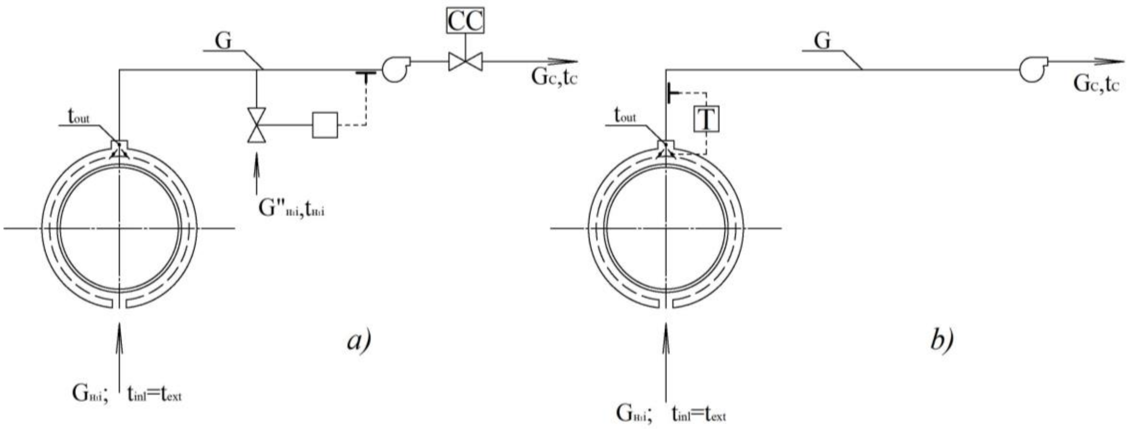

Fig. 1. Direct-flow heat extraction schemes from the rotary kiln surface:
a – option 1; b – option 2, with a bypass line; $t_{inl} = t_{ext}$ – temperature of the heat carrier at the inlet to the heat recovery device, °C; t_{out} – temperature of the heat carrier at the outlet, °C; $G'_{н,i}$ – mass flow rate of the heat carrier at the inlet, kg/h; $G''_{н,i}$ – mixed portion of the heat carrier, kg/h; G_{inc} – flow rate of the heat carrier incoming to the consumer, kg/h; t_{inc} – temperature of the heat carrier incoming to the consumer, °C; CC – consumption controller; T – temperature regulator

In these schemes, the steady heat flow is withdrawn from the kiln surface at a temperature midway between the inlet and outlet coolant temperatures, which is considered optimal for maintaining a stable external heat exchange throughout the operational period.

The bypass channel scheme (Fig. 1, b) allows for maintaining a constant coolant temperature at the outlet of the heat extraction device by using a temperature controller, while keeping the flow rate of the coolant nearly constant. This is achieved due to the structural design of the device, which enables qualitative modification of the effect of the variable part of the airflow in the outer enclosure channel on the amount of heat loss from the kiln shell surface as the flow velocity changes.

In this scheme, the stable thermal regime of the kiln can be maintained throughout the operating period using the same principle, but with improved quantitative and qualitative regulation of heat exchange on the outer surface of the kiln shell and reduced overall heat losses to the environment.

This configuration ensures a consistent flow rate of the recovered heat carrier to the consumer with minimal deviations during the entire period of operation, since the aerodynamic resistance of the overall duct system in the heat recovery unit remains unchanged – except for the resistance within the short internal channels of the device.

These internal resistances vary depending on whether the entire flow passes through the gap around the kiln or partially through the bypass line, corresponding to warm and cold periods of the year, respectively. Therefore, the mass flow rate of the coolant at the inlet and outlet of the device remains practically constant.

The inefficiency of using such schemes for the enclosed section of the rotary kiln lies in the following:

– any change in the heat carrier flow rate, depending on the outdoor air temperature, causes a change in the coolant velocity in the gap around the kiln. This affects the quality of heat transfer, i.e., the effectiveness of heat exchange on the kiln surface;

– the operation of the fan with variable air flow based on outdoor temperature must be automated with feedback on the coolant temperature after the enclosure. Moreover, as the outdoor temperature decreases, the electric motor will operate less efficiently;

– the direct-flow cooling system is not optimal for consumers of recovered heat, since the variable flow and variable temperature of the coolant rarely match the consumer's conditions and heat demand regime. As a result, it would require a large reserve capacity from a backup heat generator or would lead to excess heat being dumped into the environment – for instance, when combined with an air heating system.

Thus, although direct-flow air cooling systems for kiln enclosures are simple in design, they cannot ensure sufficient uniformity of cooling and stabilization of the thermal regime during heat recovery. Additionally, effectively using the recovered heat in rational consumer systems (such as heating or industrial processes) is quite difficult. These disadvantages can be overcome by applying a heat recovery system with a recirculation channel (Fig. 2).

This system can ensure continuous heat extraction from the kiln and is based on the reuse of the heat carrier flow, with the recirculated portion G_R increasing as the outdoor temperature t_{ext} decreases. The core principle is that, during operation, a stable temperature differential and air flow through the heat recovery device can be maintained, regardless of external air temperature fluctuations.

In the recirculation scheme, outdoor air in a volume of $G'_{н,i}$ is drawn in by fan 1, passes through the heat recovery unit 2, where it is heated, and is then supplied to the consumer 3 (e.g., for combustion air, material drying, or space heating).

Full stabilization of the heat extraction process can be achieved by maintaining a constant flow rate and temperature of the air passing through the heat recovery unit. To accomplish this, the scheme (Fig. 2) includes an automatic flow rate controller 4 and a three-way valve 5 that adjusts the proportion between the volume of outdoor air $G''_{н,i}$ and the recirculated air $G_{\delta,i}$ from the bypass line 7, ensuring that the air entering the heat utilization unit 2 remains at a constant temperature.

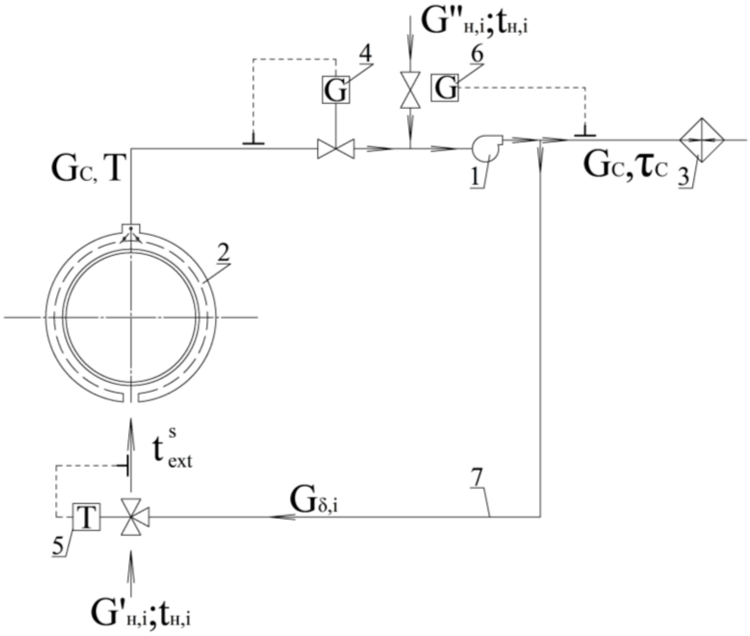

Fig. 2. Heat recovery system with a recirculation channel:
1 – fan; 2 – heat recovery unit; 3 – heat consumers; 4 – automatic flow rate controller;
5 – three-way valve; 6 – flow stabilizer; 7 – bypass line; $G'_{н,i}$ – flow rate of incoming heat carrier, kg/h; $t_{ext,i}$ – temperature of incoming heat carrier; $G_{\delta,i}$ – recirculated portion of heat carrier, kg/s; $G''_{н,i}$ – secondary intake of outdoor air, kg/s; G_c – flow rate of the heat carrier delivered to the consumer, kg/h; t_c – temperature of the heat carrier delivered to the consumer, °C

As the outdoor temperature t_{ext} changes, the amount of air flowing through the bypass $G_{\delta,i}$ also changes. To maintain a stable total airflow to the consumer G_c, a secondary intake of outdoor air $G''_{н,i}$ is introduced in a quantity $G_{\delta,i}$ equal to the bypassed volume. This secondary stream is controlled by an automatic flow stabilizer 6 to keep the supply flow constant.

The use of this heat recovery design significantly reduces material usage (e.g., less metal) and eliminates the need for thermal insulation. The system operates as follows at different times of the year.

In the summer design mode, when the outdoor temperature $t_{ext} = t_{inl}$, the system operates as a direct-flow scheme. In this case, the recirculated flow $G_{\delta,i}$ and the secondary outdoor air intake $G''_{н,i}$ are both zero (the valves of controllers 5 and 6 on the bypass line are closed). The entire airflow $G'_{н,i}$ is supplied to the consumer, i.e., $G_c = G'_{н,i}$.

In the winter design mode, characterized by $t_{ext} = t^{w}_{ext}$, the system maintains an equal flow rate of recirculated air and outdoor air intake $G_{\delta,i}=G_c$.

In transitional seasons, when $t^{w}_{ext} < t_{ext} < t^{s}_{ext}$, variable components of the total outdoor airflow always meet the condition $G'_{н,i} + G''_{н,i} = G_c$ and the ratio of $G_{\delta,i}$ to $G'_{н,i}$ is adjusted such that the temperature at the inlet to the heat recovery unit remains constant and equal to $t_{inl} = const.$

Based on the above conditions and using heat and mass balance equations, the following expressions can be derived to determine the key operating parameters of the system under consideration:

$$G_c=\frac{\alpha}{c}F\frac{\tau_{surf}-t^{s}_{ext}}{t^{s}_{ext}-t^{w}_{ext}}, \quad (1)$$

$$T=2t^{s}_{ext}-t^{w}_{ext}, \quad (2)$$

$$\frac{G'_{н,i}}{G_c}=\frac{t_{н,i}-t^{w}_{ext}}{t^{s}_{ext}-t^{w}_{ext}}, \quad (3)$$

$$\frac{G''_{н,i}}{G_n}=\frac{t^{л}_{н}-t^{i}_{н}}{t^{л}_{н}-t^{з}_{н}}, \quad (4)$$

$$G_F=2G_c. \quad (5)$$

Where:

α – heat transfer coefficient from the kiln surface to the outdoor air without a heat recovery device, W/(m²·K);

F – heat-emitting surface area, m²;

c – specific heat capacity of air, J/(kg·K);

τ_{surf} – temperature of the heat-emitting surface, °C;

t_{inl} – air temperature at the inlet to the heat recovery device, °C;

t_{ext} – outdoor air temperature, °C;

G_c – air flow rate delivered to the consumer, kg/s.

Taking the average value $\alpha \approx 30$ W/(m²·K) and dividing both parts of equation (1) by F, we obtain the specific air consumption q_{spec}, kg/s, for the heat recovery unit:

$$q_{уд} = 108\frac{\tau_{surf} - t_{ext}^{s}}{t_{ext}^{s} - t_{ext}^{w}}. \quad (6)$$

Fig. 3 shows a graph created using equations (2), (3), (4), (5) depending on the parameter φ, which characterizes the relative position of the current external air temperature on the entire scale of its calculated temperatures.

$$\varphi = \frac{t_{ext}^{s} - t_{ext}^{i}}{t_{ext}^{s} - t_{ext}^{w}}. \quad (7)$$

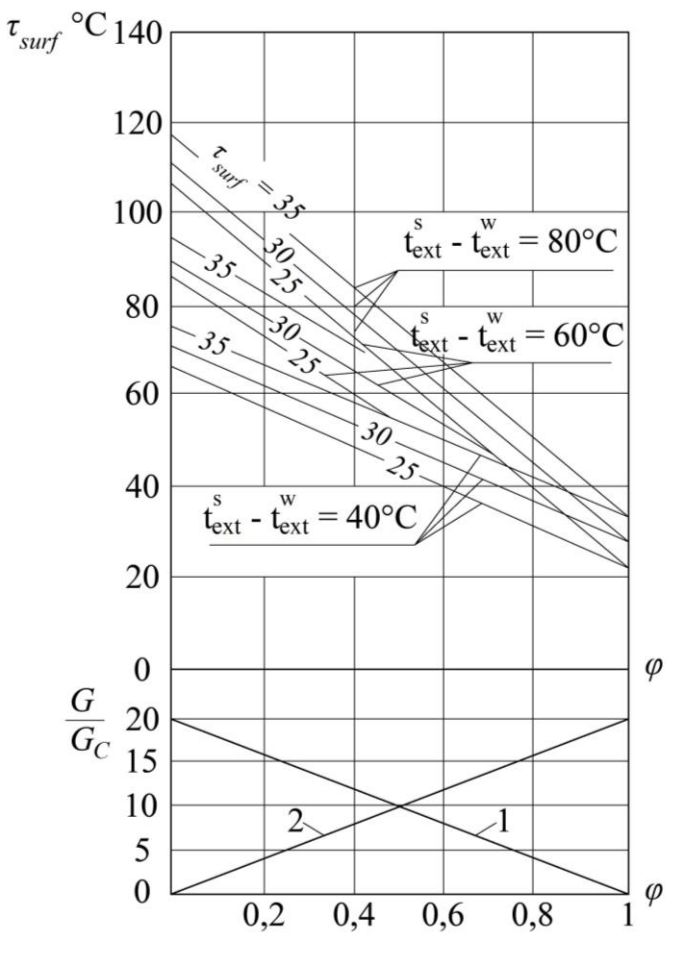

Fig. 3. Dependence of the main operating parameters of the waste disposal plant on the state of the outside temperature:

$$1 - \frac{G'_{н,i}}{G_c};\ 2 - \frac{G''_{н,i}}{G_c};\ \frac{G_{\delta,i}}{G_c}$$

From the graph, it is evident that with the same temperature on the kiln surface, the specific air flow rate increases in regions with milder climates, where the difference t^s_{ext} - t^w_{ext} between summer and winter outdoor temperatures is smaller.

Conclusions. The principles of rational cooling of rotary kilns with heat recovery for industrial heat supply were formulated. Methods for stabilizing the thermal regime and the design conditions for functional layouts of kiln units were identified.

As a result of computational and analytical research, new dependencies and relationships were established to determine the key parameters of heat recovery systems for industrial heat supply, based on the stabilizing cooling of rotary kilns.

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УДОСКОНАЛЕННЯ СИСТЕМ УТИЛІЗАЦІЇ ТЕПЛОТИ ЗІ СТАБІЛІЗАЦІЄЮ ТЕПЛОВИХ ПРОЦЕСІВ ОБЕРТОВИХ ПЕЧЕЙ

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Анотація. Статтю присвячено проблемі підвищення ефективності використання опалювальних установок для промислового і комунального теплопостачання. Сформульовано принципи раціонального охолодження печей і будівельних матеріалів, визначено способи стабілізації теплового режиму і умови розробки функціональних схем для пічних агрегатів.

Обертові випалювальні печі в умовах змінного впливу температури повітря, швидкості вітру, сонячного випромінювання і атмосферних опадів втрачають з бічної поверхні в навколишнє середовище до 30% теплоти. Несприятливий вплив зазначених факторів негативно відбивається на тепловому стані пічного агрегату з перегрівом в теплий і переохолодженням в холодний періоди року, а також знижує стійкість футерування і якість продукції. Характерно, що для підтримки необхідної температури на внутрішній поверхні печі і продовження терміну служби футерування, передбачається природне охолодження бічної поверхні агрегату. Це некерований процес з вищезазначеними недоліками.

Радикальним рішенням щодо забезпечення теплотехнологічних вимог і підвищення ефективності утилізації енергії палива, що спалюється, є організація регульованого охолодження обертової печі. Однією зі схем, що забезпечують необхідний відбір теплоти з поверхні печі, є схема з рециркуляційним каналом. Вона заснована на повторному використанні потоку теплоносія, рециркуляційна частина якого зростає зі зниженням температури зовнішнього повітря. У літньому розрахунковому режимі система працює як прямоточна і весь потік надходить до абонентських систем. У зимовому розрахунковому періоді поступає повітря з байпасної лінії.

З урахуванням вищезгаданих умов встановлено залежності для знаходження основних параметрів системи стабілізуючого охолодження обертової печі, яка використовується для комунально-побутового теплопостачання.

Ключові слова: обертова випалювальна піч, утилізація теплоти, промислове теплопостачання, повітряне охолодження, стабілізація теплового режиму.

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