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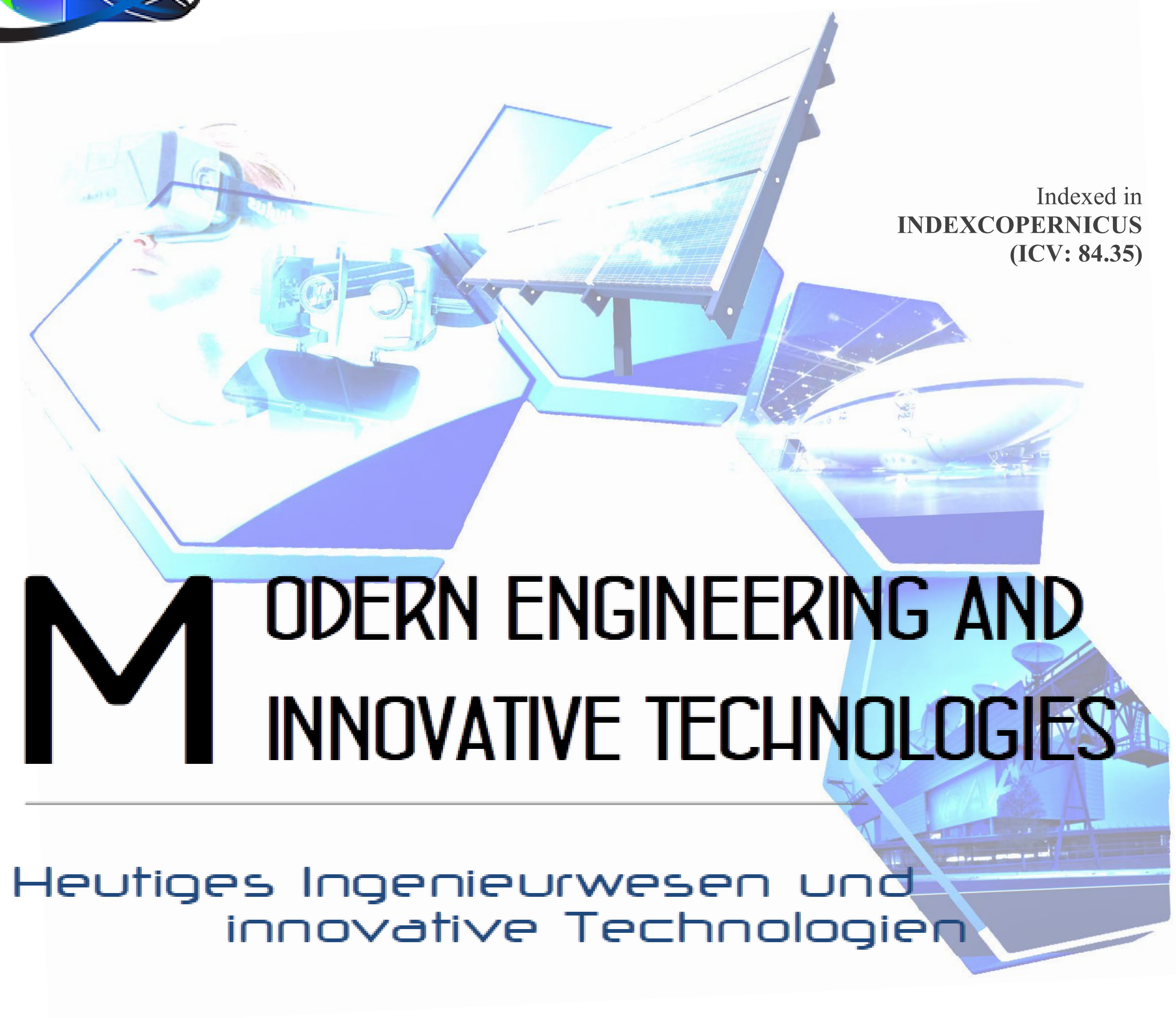

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SOME FEATURES OF CERAMIC FOAM FILTERS ENERGY EFFICIENT TECHNOLOGIES DEVELOPMENT

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Abstract. *The technological features of ceramic foam filters production of have been investigated, an effective technology for their production has been developed, as well as analysis and calculation of energy efficiency of various technologies using electric furnaces of various designs has been carried out. Feasibility study was carried out for the developed technology application in industry, depending on the relative duration, energy intensity of heating and high-temperature holding in the thermal cycle of alumina ceramics without additives of other metal oxides and with 2% additions of titanium and manganese dioxides under equivalent and real conditions of experimental laboratory production. Physical and mechanical characteristics of filters developed are given.*

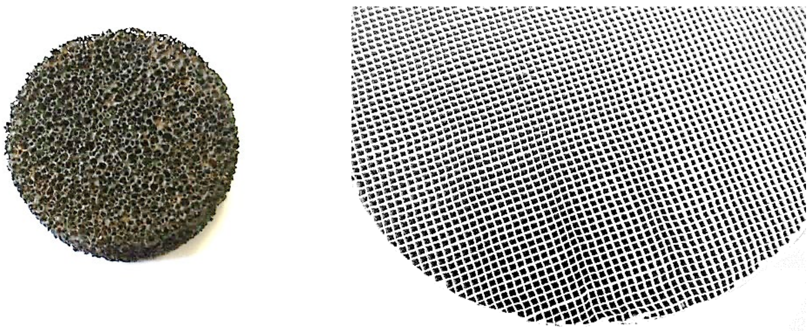
Key words: *titanium dioxide, catalyst, aluminum oxide, burning, ceramic foam filter, thermal cycle, electric furnaces, energy consumption.*

Introduction.

At present, ceramic filters are widely used in metallurgy and other industries [1, 2]. Despite their advantage in the use of high temperatures, in particular in metallurgy, thigh energy consumption of the technology for their production is obvious [3]. From this point of view, it is important not only to develop effective technologies for their production, but also to analyze the energy efficiency of the application of a particular technology in each specific case. The studies carried out in the work show that, depending on the technology used for producing ceramic filters, it is also necessary to take into account the peculiarities of using furnaces of various designs, this is extremely important, since it strongly affects the cost of the filters themselves and the technology as a whole.

Main text.

Porous structures created, both foamy (Fig. 1, *a*) and honeycomb (Fig. 1, *b*) can be used as filters for purifying various liquids and melts. On the other hand, research shows that the ceramic foam structure can be used as a catalyst carrier for afterburning of harmful vehicle exhaust gases.



a *b*

Fig. 1. Appearance of filters:
a *– ceramic foam filter;* ***b*** *– ceramic honeycomb filter*

From technological point of view, foam filters are easier to manufacture than honeycomb filters. This is due to the fact that for the production of foam filters there is no need to produce an expensive extruder which should be changed periodically. Filters with a foam structure are easier to mold due to the fact that there is no need to squeeze out the paraffinized mass through special extruder. There is also no need to distill off the paraffin. This process is usually very slow and time-consuming, which significantly reduces filter production productivity. Catalytic coating technology remains the same as with ceramic honeycomb filters. Use of submicron alumina powders allows to reduce sintering temperature and holding at the maximum temperature, which also reduces the duration of the technological cycle [4, 5].

During operation, foamy filter element must provide sufficient strength and heat resistance when purifying various metal melts. In some cases, during the burning of large foam filters, due to the temperature gradient in the furnace, cracks can form, which lead to filter breakage during operation. In order to avoid such defects, furnace lining, where the burning takes place, must provide sufficiently uniform thermal insulation.

In particular, foam filter is used for aluminum melts purification. The use of foam filters in the foundry industry provides effective trapping of non-metallic inclusions dispersed in the metal, degassing of the melt and, as a result, guarantees the production of high-quality castings with improved mechanical properties and surface quality.

A special layer, made of special catalytic coating is chemically applied to the surface of a foamy ceramic catalyst carrier to neutralize exhaust gases from internal combustion engines. Application of catalytic coatings was tested without use of expensive platinum and palladium metals.

The developed series of ceramic foam blocks (open-porous foam ceramics made of aluminum oxide modified with magnesium oxide – 2 wt%, aluminium phosphate – 10 wt%, titanium dioxide – 2 wt%, pre-burning time constitutes 1 hour) has a catalytic coating containing metal oxides compounds – molybdenum, tungsten and manganese. After blocks drying in air for 1 hour at a temperature of 250 °C, oxidative burning was carried out (at 860 °C for 30 minutes). To increase carrier surface, foam blocks were etched before applying the catalytically active layer (in 50 % nitric acid for 1 hour at a temperature of 20 °C).

The tests carried out have shown the efficiency of using foamy ceramic carriers, since the resulting branched foamy structure improves the quality of purifying. In case of ceramic honeycomb structures, expensive, complex extrusion tooling is used. From this point of view, the manufacture of foam structures is much easier. Test results showed that degree of purification of harmful emissions of the developed catalyst complies with Euro–3 standards, where great importance is given to pressure drop of gases passing through catalyst surface, since this factor greatly affects decrease in the internal combustion engine power. For this purpose, benchmark trials were carried out to determine the conditions for passage of exhaust gases through the catalyst. Results are shown in Fig. 2 and are given in table 1. According to Euro–3 standards, the resulting pressure drop, which is the difference between exhaust gases pressure at the inlet and outlet of the catalyst, is enough not to reduce engine power.

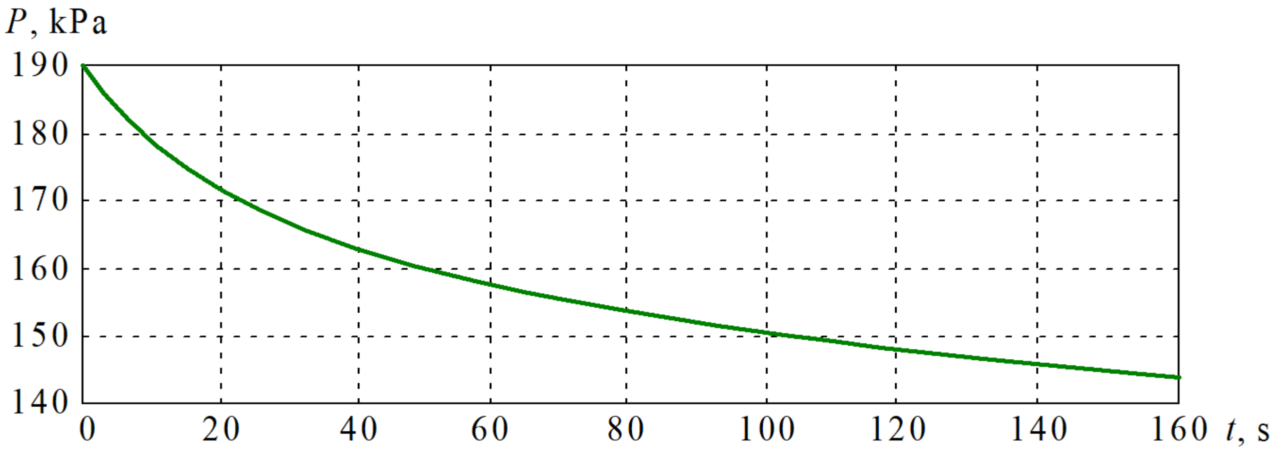


Fig. 2. Drop in exhaust gas pressure when the engine is running at 2000 rpm and power 90 N·m

Table 2 shows properties of foam filters with different porosities.

For comparison, filters by Cerapor (Germany) currently used at some Ukrainian enterprises have a compressive strength of no more than 1 MPa.

Limitation of technological process maximum temperature allows us to consider alternative options for thermal equipment for its implementation, which are less complicated and therefore more reliable, less costly at all stages of the life cycle. Transfer of heat engineering processes as a result of their improvement to lower temperatures of implementation while ensuring the necessary functionality of the manufactured product leads, as a rule, to a reduction in thermal cycle of its formation and, consequently, to production intensification [6, 7]. This fully relates to the tasks of improving the thermal cycles of sintering ceramics and corresponds to global trends in ceramic industries improvement [8, 9]. The goal is to formulate the main ways of realizing technical and economic advantages of the completed development during its development by domestic manufacturers. At the same time, we will not yet consider the financial side of the issue in absolute terms in the practice of calculations and comparisons, since modern domestic industry is developing in transitional economy, one of the characteristic realities of which is, in one way or another, manifested, including in electricity tariffs as well as in relative state financial system instability.

Table 1

Results of testing a catalyst with ceramic foam carrier that was run-in for 5 hours

	T, ºC	CO %	NO (PPM)	CH and rex (PPM)
Normal mixture				
before after % change	170 305	5.5 0.28...0.32 94 %	21.4 19.1 eight %	400 230...280 40 %
n = 2500 rpm; *N* = 19 N·m				
before after % change	380 391	1...1.2 0.01 99 %	499 16 97 %	250...260 130 49 %
n = 2500 rpm; *N* = 66 N·m				
before after % change	325 390	2.5 0.28...0.32 88 %	320 13.2 96 %	280 220 21 %
Fortified mixture *n* = 2500 rpm; *N* = 9 N·m				
before after % change	200 270	2.2...2.3 0.15...0.18 93%	70.3 14 80%	300...320 300...330 0%
n = 2500 rpm; *N* = 15 N·m				
before after % change	365 350	0.5 0.01 98 %	167.4 14 92 %	240 220 8 %
n = 2500 rpm; *N* = 20 N·m				
before after % change	365 350	3...3.3 0.03...0.04 99 %	114.3 13.7 88 %	250...260 250 0 %

Table 2

Physical and mechanical characteristics of ceramic foam filter made of aluminum oxide at sintering temperature of 1,350 °C

Indicators	Unit of measurement	1	2	3
Number of pores per 5 linear centimeters (5 ppi)	PC.	40	30	20
Compressive strength, not less than	MPa	1.6	1.4	1.4
Hydraulic resistance, no more	Pa/cm	15...80	15...80	15...80
Porosity, not less	%	75	80	80
Temperature resistance 800 ºC air, not less	Heat shifts	1	1	1
Thermal conductivity	W/m·K	0,4	0,4	0,4

To compare energy consumption of different filter ceramics technologies, the following calculation scheme was adopted. Firstly, each variant of thermal cycle is considered as a combination of heating and high-temperature holding stages (the cooling stage together with the furnace or outside of it is not considered in operation, as either one, that doesn't need any electric power support, or one, carried out with a relatively low energy consumption of such support). The sequence of stages corresponds to non-decreasing sequence of heating and high-temperature holding temperature values, specified in a certain way by process regulations.

The temperature boundaries of each *i*-th stage are such values, within which the heating intensity is kept constant and equal to some value:

$$I_i = I_i \cdot \left(T_i - T_{i-1}\right). \tag{1}$$

For the stages of high-temperature holding, $T_i = T_{i-1}$ and $I_i = 0$, in addition to I_i and T_{i-1}, is determined by the characteristics of the stage by the average temperature in the range (T_{i-1}, T_i), which we will call the equivalent temperature

$$T_{ei} = \frac{T_{i-1} + T_i}{2}, \tag{2}$$

assuming, in the general (nonlinear) case, the equality fulfillment as an equivalence criterion:

$$\int_{\tau=\tau(T_{i-1})}^{\tau=\tau(T_i)} T_{(\tau)} d\tau = T_{ei} \cdot \Delta\tau_i\ , \tag{3}$$

where τ – the current time, hour; $\Delta\tau = \tau\,(T_i) - \tau\,(T_{i-1})$, hour.

Secondly, based on well-known approaches widely used in calculating the economic efficiency of new technology, calculated (design) operating energy consumption of thermal equipment of various applications, designs and standard sizes is taken proportional to the installed capacity of the equipment.

According to the second law of thermodynamics, the elementary amount of heat δQ *is* proportional to the absolute temperature of the system T and the change in its entropy dS [10]:

$$\delta Q = k \cdot T \cdot dS\,, \tag{4}$$

where k is coefficient determined by the degree of process reversibility, $k = 1$ for reversible processes, $k < 1$ for irreversible processes.

Consequently, in the first approximation, neglecting the partial irreversibility of real thermal processes, it is fair to assume that the instantaneous absolute temperature of the system is determined by the ratio of instantaneous changes in its heat capacity and entropy. An instant (in an arbitrarily small unit of time) increase in the heat capacity of the system by an additional (external) energy-consuming (electric power) effect leads to an instant increase in the temperature of the system corresponding to the instantaneous power of such an additional effect. The resulting identification characteristic of this process with uniform (controlled) system heating at some stage of thermal cycle is the change in system temperature, determined by intensity and time of heating [11].

Thus, for each i-th stage of the thermal cycle, by analogy with equation (2) and taking into account the passport characteristics of the power N_{max} (kW) developed by the furnace and its maximum operating temperature T_{max} (°C), as well as the initial temperature T_0 (°C) furnace operating chamber in the thermal cycle, you can calculate the equivalent power N_{ei} (kW), that is, its average value:

$$N_{ei} = \frac{T_{ei} - T_0}{T_{max} - T_0} \cdot N_{max}\,. \tag{5}$$

Note that operating with the dimension of temperature °C was undertaken in this work insofar as, firstly, such an operation is possible due to the difference estimates of the temperature factor and, secondly, from the considerations that this scale is mainly used in describing thermal processes in domestic practice.

Approximation (5) allows to obtain rough estimates in conditions of uncertainty of the characteristic "instantaneous power – instantaneous furnace temperature" at idle (no load), when solving a priori predictive (design) problems associated with preliminary analysis and selection of technological solutions.

Obviously, in this case, the equality criterion is the equality

$$\int_{\tau=\tau(T_{i-1})}^{\tau=\tau(T_i)} N_{(\tau)} d\tau = N_{ei} \cdot \Delta\tau_i\,, \tag{6}$$

which at $T_0 = 0$ °C is related to expression (3) by the proportionality coefficient N_{max}/T_{max} (kW/°C), which is a complex characteristic parameter of the furnace. Expression (6) determines energy consumption for the i-th stage of the thermal cycle. For the entire heating cycle and high-temperature holding, we have:

$$W = \sum_{i=1}^{i=n} N_{ei} \cdot \Delta\tau_i\,, \tag{7}$$

where W – energy consumption, kW·hour; n is the number of stages in the thermal cycle of heating and high-temperature holding.

Parameters Tэ and Nэ, calculated for the cycle as a whole, can be used as indirect expert estimates of thermal cycles of heating and high-temperature holding. When the cycle is discretized into a finite number of stages, we have:

$$T_e = \frac{\sum_{i=1}^{i=n} T_{ei} \cdot \Delta\tau_i}{\sum_{i=1}^{i=n} \Delta\tau_i}; \tag{8}$$

$$N_e = \frac{\sum_{i=1}^{i=n} N_{ei} \cdot \Delta\tau_i}{\sum_{i=1}^{i=n} \Delta\tau_i}. \tag{9}$$

Fig. 3 shows the cyclograms of heating and high-temperature holding in intensified thermal cycles of the production of alumina ceramic filters.

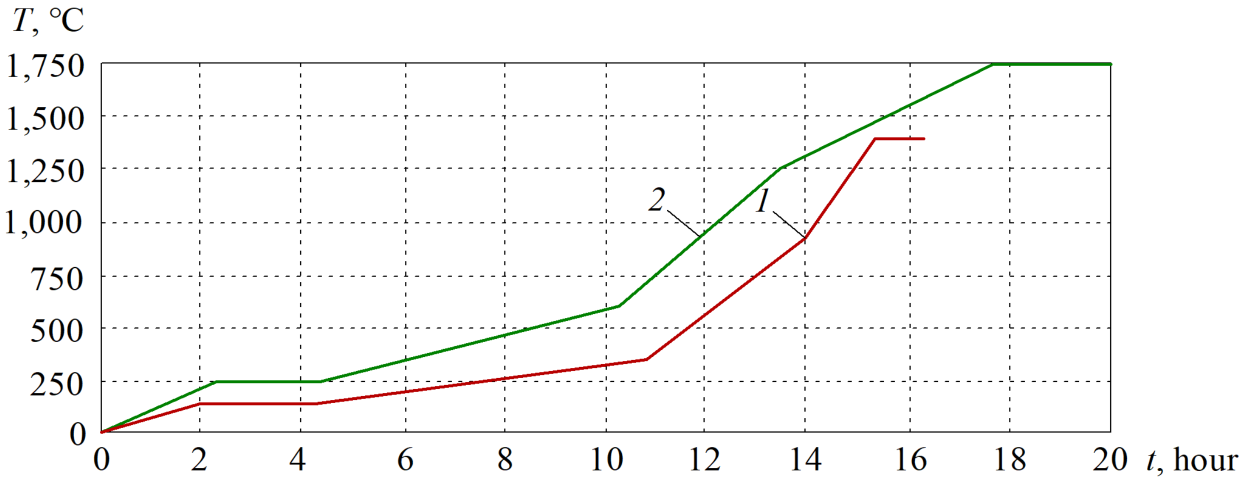


Fig. 3. Cyclograms of heating and high-temperature holding in thermal cycles of porous alumina ceramics technologies without additives of other metal oxides (*1*) and with two percent additions of titanium and manganese dioxides (*2*)

From comparison of cyclographic characteristics of the temperatures and times necessary and sufficient for the formation as a result of heating and high-temperature exposure, which are functionally successful in the refining of liquid aluminum, alumina other metal oxides and by the technology with two percent additions of titanium and manganese dioxides, there is unconditional advantage of the second technology.

The completion time of its heating cycle and high-temperature holding (16.2 hours) is 19 % shorter, and the maximum temperature in the cycle (1,350 °C) is 20 % less, which allows the use of simpler and less power-consuming furnace equipment.

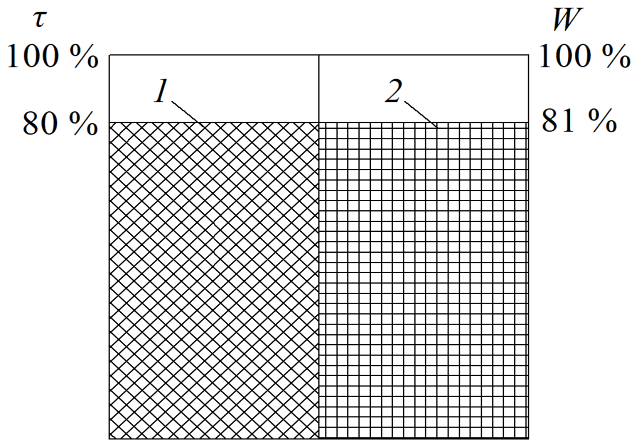
Table 3 shows some operating characteristics of these thermal cycles, as well as furnaces used in their implementation in experimental laboratory production; here and under the same (comparable) conditions, typical analogue (with the addition of 13 % chromium oxide), considered in [12] when developing intensified technologies, was determined. According to these operating characteristics and the accepted design scheme using dependencies (2), (5) and (6), respectively, the values of T_{ei}, N_{ei} and W_i were obtained for the heating and high-temperature holding stages for each of the technologies.

Table 3

Power consumption and energy consumption in the thermal cycle of various technologies of porous alumina ceramics in real conditions of experimental laboratory production

Technology	Characteristics of the laboratory furnace		Characteristics of technology stages	Sequence of heating and high-temperature holding stages					
	Maximum working temperature, °C	Maximum power, kW		I	II	III	IV	V	VI
Typical with 13 % Cr_2O_3 additive	1,400	2.5	Stage duration, hour	1.75	1	12.5	1	14.15	5
			Average temperature, °C	72.5	125	312.5	500	925	1,350
			Average power, kW	0.1	0.19	0.53	0.87	1.64	2.41
			Energy costs, kW·h	0.17	0.19	6.62	0.87	23.2	12.05
Intensified without metal oxide additives	2,500	35	Stage duration, hour	2.3	2	5.8	3.25	4.15	2.5
			Average temperature, °C	135	250	425	925	1,500	1,750
			Average power kW	1.62	3.25	5.72	12.77	20.89	24.42
			Energy consumption, kW·h	3.73	6.49	33.15	4.51	86.68	61.04
Intensified with additions of 2 % TiO_2 + 2 % MnO_2	1,400	2.5	Stage duration, hour	2.15	2	6.65	3.05	1.35	1
			Average temperature, °C	85	150	250	625	1,150	1,400
			Average power kW	0.12	0.24	0.42	1.1	2.05	2.5
			Energy consumption, kW·h	0.25	0.47	2.77	3.34	2.76	2.5

Fig. 4 illustrates resulting advantages of relatively low-temperature technology using two percent additions of titanium and manganese dioxides over the technology of monoxide corundum ceramics in terms of time and energy consumption of heating and high-temperature holding. Here, let us pay attention to the fact that under equivalent conditions of experimental laboratory production, that is, with the use of a deliberately less economical replacement for a vacuum furnace (N_{max} = 35 kW, T_{max} = 2,500 °C), which is, if necessary, used in the production of ceramics only from aluminum oxide, the advantages of the considered polyoxide technology in terms of energy consumption of heating and high-temperature holding also remain very significant.



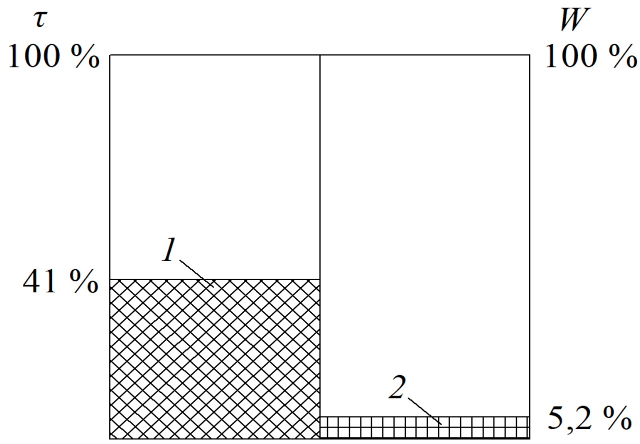


Fig. 4. Relative duration (τ) and energy consumption (*W*) of heating and high-temperature holding in the thermal cycle of alumina ceramics without additives of other metal oxides (100 %) and with two percent additions of titanium and manganese dioxides under equivalent (*1*) and real (*2*) experimental conditions of laboratory production

Calculated total energy savings with the adoption of a polyoxide technological alternative is 41 % in comparable technical experimental laboratory conditions (furnace parameters: $N_{\max}$ = 35 kW, $T_{\max}$ = 2,500 °C) and 5.2 % – under conditions of burning alumina ceramics using additions of titanium and manganese dioxides in a furnace with $N_{\max}$ = 2.5 kW, $T_{\max}$ = 1,400 °C.

If the comparison of energy consumption of analyzed technological solutions is carried out only according to the maximum power consumed by the furnace, as is suggested by traditional methods, for example, [13], then assessment of relative energy consumption of the polyoxide alternative in comparable and real experimental laboratory conditions will be 81 % and 5.2 % respectively.

Discrepancy between absolute estimates of energy consumption of the cyclograms implementation in Fig. 4 for mono- and polyoxide ceramics in terms of maximum and equivalent power is determined by ratio $N_{\max}/N_e$ and at T_0 = 20 °C will be more than 200 % for monoxide technology assessment (200.9 %) and for polyoxide technology assessment (233.3 %). Thus, it is obvious that the use of the proposed calculation technique in forecasting and analyzing indicators of thermal cycles can significantly increase reliability of expert assessments.

Note that from Table 3 and from accepted design scheme, we obtain the following quantitative characteristic of advantages of intensified technology of alumina ceramics using two percent additions of titanium and manganese dioxides over a similar technology with 13 % addition of chromium oxide (T_0 = 20 °C): in terms of productivity (excluding the cooling stage) – more than 2 times (with durations of heating stages and high-temperature holding, respectively, 16.2 hours and 35.4 hours), in terms of energy consumption – more than 3.5 times (12.1 kWh·hour and 43.1 kW·hour respectively).

Let us consider two circumstances, the influence of which is less significant on the final technical and economic results of production, but which, if necessary, should also be taken into account (and controlled). The first is connected with the thermal cycle initial stage, namely, the effect of its initial temperature T_0. The second is the cooling stage. As we can see from Table 3, lowering the initial temperature of the thermal cycle from 20 °C to 0 °C in each of the considered technological options, that is, lowering the lower limit of the thermal cycle with an expansion of its temperature range by 1.2 % for technology without metal oxide additives and by 1.5 % for technology with two percent additions of titanium and manganese dioxides, causes a decrease in equivalent temperatures values (by 1 % and 2 %, respectively) and an increase in equivalent capacities (by 0.6 % and 1.3 %, respectively). As a result, energy consumption increases, moreover, faster than the expansion of temperature ranges in thermal cycles, namely by 1.6 % and 3.5 %, respectively. This leads to two useful conclusions.

First: maintaining the normal temperature status of industrial premises has a positive effect on economics of thermal processes in these premises. Second: to increase periodic thermal production efficiency, it is advisable to use residual heat of furnaces, for which, in improving their designs and technological operating procedures, developments aimed at reducing the auxiliary time for unloading and loading are especially useful. Double attention should be paid to this issue both from the point of view of reducing the heating time and, accordingly, reducing level of energy consumption (Table 4), and from the point of view of increasing the share of productive time in the entire furnace operating cycle.

Table 4

Resulting estimates of heating cycle and high-temperature holding at various values of thermal cycle initial temperature

Technology	Furnace characteristics		Initial temperature T_0, °C	Estimates			
	T_{max}, °C	N_{max}, kW·h		T_e, °C	N_{max}, kW·h	W, kW·h	$\Sigma\Delta\tau_i$, hour
Intensified without metal oxide additives	2,500	35	0	835.8	11.7	236.37	20.2
			20	844.1	11.63	232.61	20
Intensified with additions of 2 % TiO_2 + 2 % MnO_2	1,400	2.5	0	423.5	0.76	12.52	16.55
			20	432.3	0.75	12.1	16.2

Note that reducing the heating time $\Delta\tau_0$ (hour) at the first stage of the thermal cycle due to an increase in its initial temperature by an amount ΔT_0 (°C) at a given heating intensity I_1 (°C/hour) will be determined from the ratio (Fig. 5):

$$\Delta\tau_0 = \frac{\Delta T_0}{I_1}. \tag{10}$$

Cooling stage in the work was not considered in detail for the reason that it is not energy-intensive: cooling of ceramic products after annealing with heating and high-temperature holding is controlled and carried out together with the furnace, and, as a rule, at the maximum possible speed (up to 2.5 °C/s).

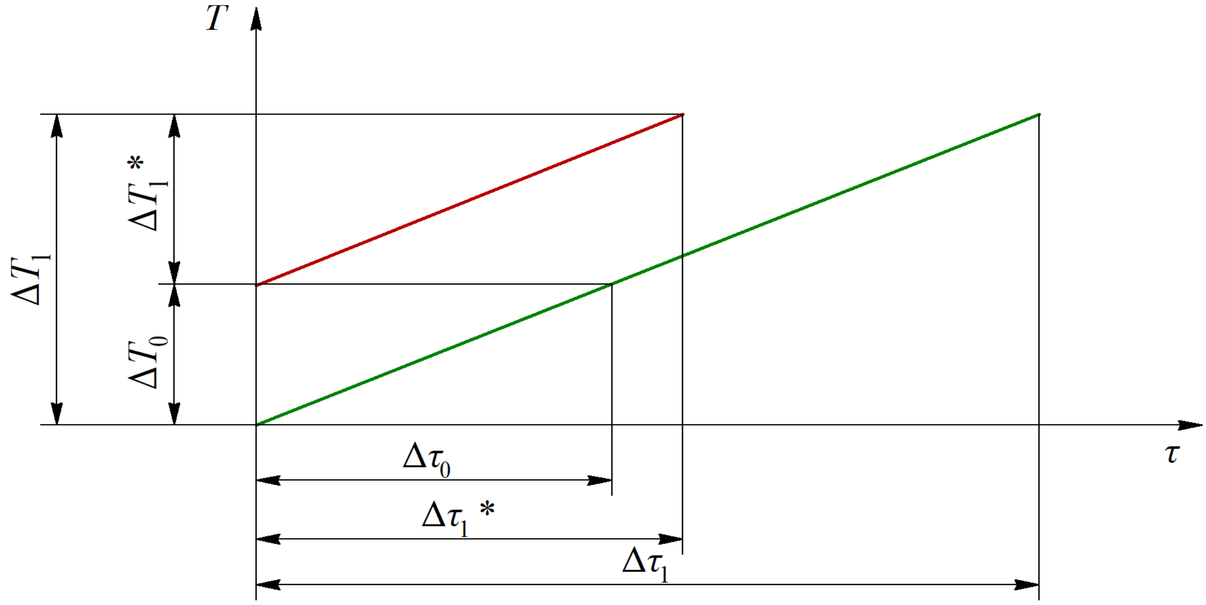


Fig. 5. To calculation of the first stage of heating in variations of the initial temperature (T_0* > T_0) at a given heating intensity (I_1 = const)

Slowing down the furnace cooling by a gradual decrease in electrical power is usually not required, but even with a fivefold margin of maximum possible cooling rate, this stage in intensified technologies of alumina ceramics takes 4.8 % and 4.7 % of heating time and high-temperature holding according to cyclograms, respectively, for monoxide and polyoxide ceramics (Fig. 3). Therefore, the share of energy consumption for cooling in a complete thermal cycle is very small, if not zero. Reducing of auxiliary time for furnace loading and unloading in complete ceramic production cycle can be achieved by using bogie bottom designs such as Mobilotherm furnaces. Unlike conventional chamber furnaces, in these applications, the bottom of the furnace (bogie hearth) is charged outside the furnace.

Reduction in the volume of furnace unproductive operating time is ensured due to the fact that for each furnace two hearths are simultaneously used: when one of them is in the furnace, the other can be loaded. Since the exchange of bogie hearths requires a fairly short time, which is practically independent of the volume of the hearth load, the use of a bogie hearth system practically means no stove downtime. This mechanism of using the bogie hearth system, due to the reduction in the time for unloading and loading the furnace, also allows a greater use of residual heat, which is especially manifested in the operation of large furnaces with full load. Standard furnace can be opened up to approx. 500 °C; if it is necessary to do this at higher temperatures, a furnace with a lifting door and a sliding rail hearth can be used.

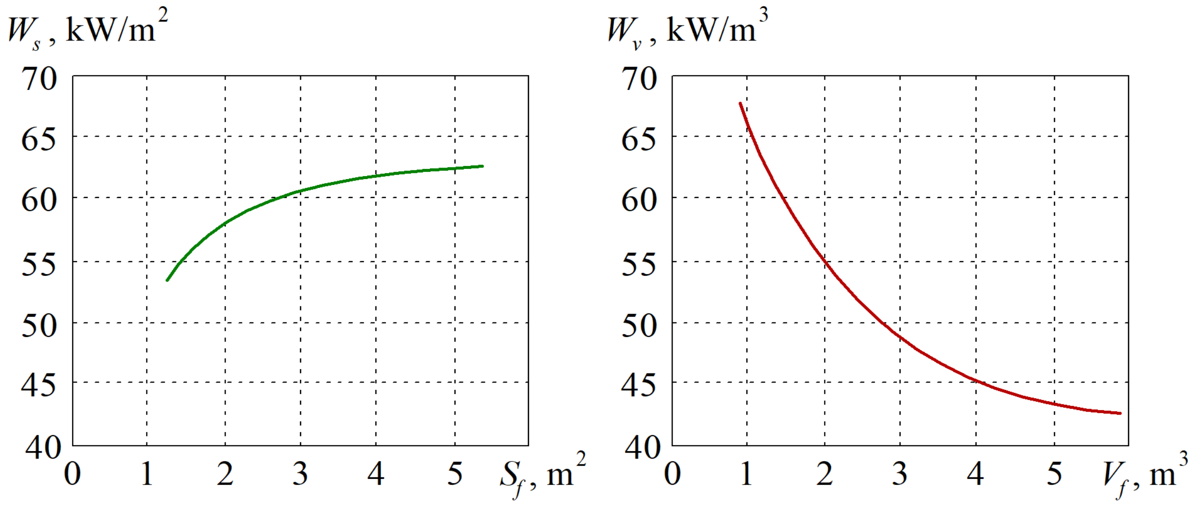
Further, let us pay attention to the fact that with increase in furnace chamber internal dimensions, the ratio of the maximum power consumption N_{max} (kW) to the furnace hearth area S_f (m^2), or the power W_s distributed over hearth area (kW/m^2) changes to relatively small extent with a change in hearth area.

With a change in hearth area approximately twofold around the average value in the presented model range of Mobilotherm furnaces, which we will assume corresponding to model W3300/14 (S_f = 2.8 m^2), value W_s changes within 10 % (Fig. 6, *a*). Therefore, at single-tier furnace loading, the use of this change in the interests of energy costs saving per unit and entire production output is relatively insignificant.

For example, in the manufacture of a batch of products, the overall dimensions of which were 380×380×50 mm^2 with internal dimensions of laboratory furnace chamber 400×400×450 mm^2, and which were intended for industrial filtration of liquid aluminum, if this batch were made in Mobilotherm furnaces, then, when changing from model W1000/14 to model W7500/14 with the same utilization of the hearth area in terms of one product as in laboratory conditions ($k_{us} \approx 0.9$), production of filters in one thermal cycle of furnace increases from 8 to 26 items, or by 225 %, with increase in total energy consumption by almost 5 times, or almost 1.5 times in terms of one item.

On the other hand, with furnace chamber internal dimensions increase, that is, furnace volume, the ratio of maximum power consumption N_{max} (kW) to furnace operating volume V_f (m^3), or specific power W_v (kW/m^3), changes to a much greater extent (Fig. 6, *b*) within the considered range of furnace models. With increase in the furnace operating volume from $V_f = 1.024$ m^3 to $V_f = 7.56$ m^3, or approximately 7.4 times, specific power decreases by more than 1.5 times, which in some cases makes it possible to consider expediency of multi-tiered furnace loading, especially with interchangeable bogies if product dimensions and design of the shape containing it allow such loading.

So, when solving the production problem considered above and corresponding to [15, 16], taking the values of hearth area and height utilization coefficients in terms of one product, respectively, $k_{us} = 0.9$ and $k_{uh} = 0.5$, within the range of furnace models under consideration, it is possible to increase filters output in one thermal cycle of the furnace from 64 to 364 items, or by about 470 %, and with a decrease in energy consumption per item, in our case, about 15 %.



a *b*

Fig. 6. Factual account of dependences of power W_s distributed over the area from hearth area S_f (*a*) and specific power W_v on internal volume V_f (*b*) for a range of Mobilotherm furnace models designed for burning ceramics with maximum operating temperature T_{max} = 1,400 °C

Along with operating chamber dimensions, the fundamental design features of the burning unit can no less significantly determine the amount of energy consumed by various burning units with maximum operating temperature:

– bogie hearth furnace – 100 %;
– conventional tunnel furnace – 93 %;
– furnace with upper and lower burners, with trolleys with light refractory lining for accelerated burning – 61 %;
– furnace for accelerated burning with upper burners and a moving hearth – 50 %;
– roller furnace – 31 %.

From the presented it follows that decrease in energy consumption during burning can be achieved by complicating furnace design, which means an increase in their selling price and unproductive operating costs. From the consumer's point of view, economic feasibility of using such a progressive, but expensive equipment arises with a sufficiently large volume of orders and stable demand. In addition, with the use of increased complexity equipment, additional issues of its technological systems reliability redundancy arise, the solution of which is also associated with additional costs, that are more justified, the larger and more stable the scale of production is [17].

It should be noted that a slightly higher level of specific energy consumption when using moving hearth furnaces without additional top burners compared to conventional tunnel furnaces, due to the possibility of more efficient use of residual heat, as noted earlier, is to some extent compensated for in the overall structure of energy consumption in-line production (which is, moreover, more productive when using the bogie-hearth exchange scheme unloading and loading the furnace).

Conclusion and findings.

On the basis of the performed experimental and laboratory development and research of energy-saving production technologies of porous permeable alumina ceramics, which have passed industrial testing as filters for purifying liquid aluminum, and also taking into account global trends in improving equipment and technologies for similar applications, a number of directions for additional reduction of energy consumption for the production of one products and increasing the productivity in the industrial development of the proposed technologies.

When designing and forecasting new and reconstructed ceramic industries, it is recommended, in particular, to pay attention to structural, geometric, temperature and energy features and capabilities of the furnaces, considered in conjunction with the structural and parametric characteristics of mastered technological regulations. To carry out *a priori* comparative assessments of energy consumption and fundamental technological polyvariants and technical environment for their possible implementation, a design scheme is proposed, which is used in analysis of specific situations. The nearest prospect of further development of ceramic filters for the liquid aluminum metallurgy, including those based on alumina, should apparently be considered, first of all, as the industrial development of experimental and laboratory developments performed.

Basing on the material presented in the work, the following conclusions can be made.

1. Carried out tests have shown the effectiveness of foamy ceramic carriers use, since the formed branched foamy structure improves purifying quality.

2. Tests of catalyst support blocks made on the basis of foam structures have shown that they provide required pressure drop in exhaust gases and required degree of purification of carbon monoxide and nitrogen in accordance with Euro–3 standards.

3. Developed foam filter can be used both as catalyst carriers and in the metallurgical industry for purifying melts of aluminum, copper, steel, and cast iron. Use of foam filters in foundry industry provides effective trapping of non-metallic inclusions dispersed in the metal, melt degassing and guarantees production of high-quality castings with improved mechanical properties and surface quality.

4. Economic assessment of use of electric furnaces of various designs has been carried out and an energy-efficient technology for producing ceramic filters has been proposed on the basis of analytical formulas.

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Аннотация. *Исследованы технологические особенности получения пенокерамических фильтров, разработана эффективная технология их получения, а также проведен анализ и расчёт энергоэффективности различных технологий с применением электрических печей различной конструкции. Проведено технико-экономическое обоснование применения разработанной технологии в промышленности в зависимости от относительной длительности, энергоёмкости нагрева и высокотемпературной выдержки в термическом цикле алюмооксидной керамики без добавок других металлооксидов и с двухпроцентными добавками диоксидов титана и марганца в эквивалентных и реальных условиях опытно-лабораторного производства. Приводятся физико-механические характеристики разработанных фильтров.*

Ключевые слова: *диоксид титана, катализатор, оксид алюминия, обжиг, пенокерамический фильтр, термический цикл, электрические печи, энергозатратность.*