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Smart Sustainable Production Management for City Multifloor Manufacturing Clusters: An Energy-Efficient Approach to the Choice of Ceramic Filter Sintering Technology

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Abstract: The development of environmentally friendly technologies, including additive technologies, contributes to the formation of sustainable production in city multifloor manufacturing clusters (CMFMCs). This paper discusses an approach to the implementation of energy-intensive technological processes in such clusters using examples of the manufacturing of ceramic and metal–ceramic products. The manufacturing of ceramic and metal–ceramic products in high-temperature furnaces is associated with an increased electricity consumption. The use of modern ceramic micro- and nanopowders makes it possible to switch to more energy-saving technologies by reducing the sintering temperature and shortening the technological cycle. This requires the use of additional activating and inhibiting additives in the initial powder mixtures to obtain products with the necessary physical and mechanical properties. The purpose of this paper is to present a model and indicators to assess the energy efficiency of the choice of sintering technology of foam ceramic filters for smart sustainable production management within CMFMCs. The use of the proposed indicators for assessing the energy efficiency of sintering foam ceramic filters makes it possible to improve the technological process and reduce the completion time of its thermal cycle by 19%, and reduce the maximum heating temperature by 20% to 1350 °C. The adoption of a different oxide technological alternative and the use of the proposed model and indicators to assess the energy efficiency of the sintering technology of foam ceramic filters allows to choose less energy-intensive equipment and save up to 40% in electricity. The proposed model to assess the energy efficiency of the sintering technology of foam ceramic filters can be used to control their production under the power consumption limitations within the CMFMCs.

Keywords: city multifloor manufacturing; smart sustainable production management; foam ceramic sintering; high-temperature furnace; energy-efficient thermal cycle

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1. Introduction

One of the modern approaches to the organization of manufacturing in large cities is the creation of city multi-floor manufacturing clusters (CMFMCs). CMFMCs are an association of a group of multi-floor manufacturing buildings and a city logistics node serving them, which are located in the same residential area of a large city [1,2]. Small- and medium-sized enterprises of CMFMCs are the main producers of goods and products for the population of the cluster, the city and its industrial enterprises [3,4]. A comprehensive rapid satisfaction of the consumers' needs of CMFMC products is associated with the expansion of its range, an increase in the share of innovative goods and the use of modern smart and sustainable technologies, primarily additive technologies [1,4]. The expansion of the range of manufactured products in the cluster is possible through the use of energy-intensive industries, which include the production of ceramics [5,6]. The main problem of organizing energy-intensive production in a CMFMC is the limited possibilities of its energy consumption. Reducing the energy consumption of such technologies is a high-priority task, the solution of which opens up wide opportunities for the use of various ceramic technologies in CMFMCs.

One of the products of such CMFMCs is foam ceramic filters that are sintered at high temperatures [5,6]. Limiting the maximum process temperature to 1400 °C allows for the use of furnaces with more reliable and cheaper silicon carbide heaters [5]. The use of less energy-intensive technological processes in clusters is of great interest in terms of increasing their energy efficiency.

Improving the thermal engineering processes of sintering foam ceramic filters by reducing the temperature of their flow and, at the same time, providing the necessary quality characteristics of the finished product lead to a reduction in the thermal cycle of manufacture and, consequently, the intensification of production. This fully relates to the tasks of improving the thermal cycles of sintering ceramics and corresponds to the global trends in improving ceramic production. From this point of view, in addition to conventional sintering, microwave sintering is of particular interest [7,8]. The use of additive technologies for the production of ceramics further increases the possibilities of using high-temperature furnaces in CMFMCs [3,9].

Energy management is one of the fundamental factors of the production organization within CMFMCs, which ensures the energy efficiency of manufacturing under the limitation of energy consumption [10,11]. Energy management models and practical recommendations for their application within CMFMCs are in their infancy. Despite the increased interest in energy efficiency in city manufacturing, energy management is still a subject of further research in order to eliminate existing gaps in the literature [10–15].

The purpose of this paper is to present a model and indicators to assess the energy efficiency of the choice of sintering technology of foam ceramic filters for smart sustainable CMFMCs. The use of the proposed model and indicators to assess the energy efficiency of the sintering technology of foam ceramic filters makes it possible to support management decisions aimed at reducing the energy consumption of the sintering process, as well as reducing the completion time of its heating cycle and high-temperature holding.

The remainder of this paper has the following structure: Section 2 presents a literature review of smart sustainable ceramic filter sintering technology and processes within CMFMCs. Section 3 presents the materials and methods, including the proposed model and indicators for the energy efficiency assessment of the choice of sintering technology for ceramic foam filter materials. Section 4 presents the research results and their discussion. Section 5 contains the managerial implications. Lastly, the final conclusions are presented in Section 6.

2. Literature Review

2.1. Smart Sustainable Production Management of Ceramic Materials within CMFMCs

Smart sustainable city manufacturing consists of intelligent production and transport systems integrated with information and communication technologies and socio-cyber-physical systems that solve production and logistics tasks in real time in order to meet the needs of consumers through economically, socially and environmentally sound processes within the closed-cycle economy that minimize the negative impacts on the environment, health of citizens and society, while conserving energy and natural resources [3,16–21]. Smart sustainable city manufacturing is supported by the emergence of the information society, change in quality of labor resources and increase in consumer demand for innovative sustainable products and services [22,23]. Therefore, the activities of CMFMCs aim at creating such products and services for the population and enterprises of the agglomeration in conditions as close as possible to labor resources and consumers [3,22].

The possibility of organizing the manufacturing of products in CMFMCs for the population and enterprises of the agglomeration is associated with general trends of the miniaturization of goods and the efficient use of natural and energy resources for circular economy implementation [3,21,22,24]. The production of such goods is carried out using, as a rule, lightweight small-sized technological equipment, which can be delivered to production floors of the CMFMC buildings in assembled form by means of freight elevators [3]. Large-sized technological equipment is used in a modular design [1,25], mainly of a lightweight frame structure [26], and is delivered modularly to the production floor by freight elevators with their subsequent assembly in the workshop [3]. The technological equipment, materials and component delivery to production enterprises of CMFMCs and the finished products and industrial waste shipment from them are carried out mainly through the city logistics node of the cluster by means of intelligent reconfigurable trolleys [1,27]. This approach to the organization of production in CMFMCs is basic and does not take into account the specifics of using energy-intensive productions. This study attempts to eliminate this gap. As an energy-intensive production within CMFMCs, the paper discusses the technological process of sintering foam ceramic filters.

Foam composite filters can also be attributed to innovative small-sized products [5,6]. The sintering of foam composite filters is carried out in high-temperature furnaces, which can be used within the framework of smart sustainable CMFMCs. In this study, the sintering of foam composite filters was carried out in Nabertherm furnaces (Germany), which have reasonable, stable, intelligent and sustainable technology characteristics with the ability to control and monitor the process, and can be used within CMFMCs. Nabertherm furnaces are equipped with controllers that implement control and process monitoring, display user levels and the program status, the graphs of temperature curves of the selected program, the precise temperature control at different stages of sintering, etc. [6].

The sintering of foam composite filters is an energy-intensive process, which makes it difficult to use in a sustainable CMFMC under the limitations of the power system. Therefore, it became necessary to study the possibility of reducing electricity consumption during the sintering of foam composite filters by improving the technological process based on an energy-efficient approach.

2.2. Ceramic Filter Sintering Processes: An Energy-Efficient Approach

Currently, various filtration systems are used in city manufacturing and industries to purify liquids and gases from mechanical impurities and harmful atmospheric emissions. The main element of these systems is the foam composite filter, which, depending on the cleaning medium, must have a certain permeability [28–31].

The creation of filters from various ceramic materials in relation to a particular medium is of great practical and scientific interest. It is assumed that the use of nanodispersed and submicron powders in the molding and sintering of permeable, porous materials can reduce the sintering temperature of refractory materials and increase the cleaning efficiency, while providing high physical and mechanical characteristics [32,33].

In most cases, when using porous ceramics, both their structural and functional capabilities are used. The correct combination of functional and physico-mechanical properties, which are largely determined by the microstructure of the material, allows to obtain optimal performance of products [34–36].

As a result of technical progress in ceramic production technology, it has become possible to obtain sintered materials with a finer texture and precise dimensions, single crystals, and thin films [37–40]. Ceramic materials obtained using modern, often nontraditional, technologies have properties determined by their microstructure. Such properties of these materials, such as adsorption, permeability and ability to separate substances, etc., depend on their porosity. At the same time, it is necessary to provide these materials with such mechanical properties as, first of all, strength, which can guarantee the desired performance and functionality. Porous ceramics intended for filters should be characterized by high chemical resistance to aggressive media and elevated temperatures. The high strength of porous ceramics makes it possible to operate them at sufficiently high pressures [41].

Porous ceramics have a body composed of firmly interconnected grains of ceramic material. The grains have certain sizes, and in the vast majority of cases, the connection between them is carried out using clay materials. In some cases, the grain sintering of the same nature is carried out without a binding component. The porous materials are subdivided into single- or multicomponent, which are created on the basis of some refractory oxide with or without various additives [42,43].

The ceramic material is a combination of a solid substance (crystalline and vitreous) with voids–pores. The volume of pores, their size and the nature of distribution have a decisive influence on both the mechanical and functional properties of products. Porous ceramics are an important filter material for gases and liquids, and its mechanical and functional properties for this are crucial [44,45].

The porosity value determines the fundamentally important separation of all ceramic materials into sintered and porous. The formal sign of sintered building ceramics is considered to be the apparent porosity of less than 2%, and a refractory porosity of 3%. However, in fact, for sintered ceramics, which primarily include vacuum ceramics and porcelain, an apparent porosity of less than 0.1...0.2% is a sign of complete sintering.

In the manufacture of large and complex products, additives with grains of various sizes (up to 2...3 mm) are introduced into the molding mass. This reduces the shrinkage of products during sintering and increases their heat resistance, although, at the same time, the porosity increases and the strength decreases. The high porosity of thermally insulating filter ceramics is achieved by introducing burnable or foaming additives into the initial powders, as well as porous fillers with a certain grain size. From this point of view, it is interesting to create foamy porous structures using nanopowders. The technological processes for obtaining permeable composite materials, especially from submicron and nanoparticles, are currently insufficiently studied.

The sintering of multicomponent dispersed mixtures is a more complex process, which differs significantly from the sintering of single-component mixtures [46]. As a result of sintering multicomponent batches, the structures formed are solid solutions, chemical compounds and heterogeneous mixtures of pure components. The creation of an optimal structure is the most important problem of obtaining materials with specified physical and mechanical properties. The complexity of obtaining porous materials with specified properties lies in the fact that, in some cases, it is necessary to prevent the occurrence of negative processes (diffusion, recrystallization or dislocation movement) and, at the same time, to introduce components incompatible with each other into the composition, preventing their interaction and ensuring the achievement of required properties for the finished product.

Ceramic sintering is one of the most complex technological operations, as it is accompanied by phenomena such as shrinkage or growth of compacts, chemical reactions and fusion of components. Ultrafine powders cause large shrinkage during sintering, and this shrinkage process is faster than traditionally used powders. Volumetric changes are significantly affected by the preliminary density of pressing samples. Shrinkage during the sintering of products decreases with an increase in the density of pressing samples, but, in some cases, the consequence of pressing samples is their expansion. The rate of heating and the composition of the medium chosen have a great influence on this phenomenon. Fine powders retain a greater amount of absorbed gases and air than coarse powders, so the heating of fine powders must be started slowly so that there is enough time to remove the gases.

The use of nanodispersed and submicron powders in the creation of porous ceramics makes it possible to obtain materials with a very fine texture and precise dimensions. The obtained materials have properties corresponding to their structure, such as adsorption, ion exchange, permeability, separation ability and others [47,48]. Among the properties that characterize porous bodies, it should be noted the usual porosity is characterized by lightweight products and the creation of uniform tiny holes in products. Another way is to produce ceramic materials using substances that dissociate and volatilize during heat treatment, such as hydrates, carbides, etc. These products are used as catalyst carriers. In this case, microholes are obtained in the range from several nanometers to several tens of nanometers. At the same time, the complexity of obtaining the porous ceramics with hole diameters in a relatively narrow range should be noted. No less significant are the issues of obtaining permeable structural ceramics with a relatively large pore size from submicron particles. In this case, it is possible to significantly reduce the sintering temperature and reduce the time of the technological process.

The use of submicron and nanopowders significantly activates the sintering process, which allows to significantly reduce the sintering temperature and shorten the technological cycle of manufacturing foam ceramic filters. This helps to reduce energy consumption in the production of foam ceramic filters within CMFMCs.

Thus, it can be assumed that the use of submicron particles in the creation of permeable filtering ceramics can make it possible to create products with a high level of efficiency and physico-mechanical characteristics. Based on this, the following research objectives were set:

- To develop a model and indicators to assess the energy efficiency of the choice of sintering technology for foam ceramic filters for smart sustainable CMFMCs.
- To investigate the possibilities of relatively low-temperature technology using two percent additives of titanium and manganese dioxides before the technology of monoxide corundum ceramics in terms of time and energy intensity of heating and high-temperature holding.
- To offer recommendations for operators/managers of production of foam composite filters on the choice of energy-efficient technologies and appropriate equipment for their application within the framework of smart sustainable CMFMCs.

3. Materials and Methods

The foam ceramic filters were manufactured using submicron aluminum oxide powders of two phases, γ and α (produced by Zhengzhou YUFA Abrasives Group Co., Ltd., China), with the characteristics given in Tables 1 and 2. The sintering of foam ceramic filters was carried out in Nabertherm (Germany) furnaces, shown in Table 3. All Nabertherm furnaces presented in Table 3 were laboratory furnaces, but could be used for the production of small batches of parts.

Table 1. Characteristics of γ-Al_2O_3.

N/N	Name of Characteristics	Percentage (%)
1	Fractional composition:	
	0.3 … 0.4 (μm)	50.0
	0.2 … 0.3 (μm)	30.0
	0.1 … 0.2 (μm)	14.0
	Less than 1 (μm)	6.0
2	Content of the main impurities:	
	Fe_2O_3	0.003
	Na_2O	0.001
	SiO_2	0.010
	TiO_2	0.002

Table 2. Characteristics of α-Al_2O_3.

N/N	Name of Characteristics	Percentage (%)
1	Fractional composition:	
	0.3 … 0.4 (μm)	45.0
	0.2 … 0.3 (μm)	25.0
	0.1 … 0.2 (μm)	23.0
	Less than 1 (μm)	7.0
2	Content of the main impurities:	
	Fe_2O_3	0.003
	Na_2O	0.001
	SiO_2	0.011
	TiO_2	0.002

Table 3. The main characteristics of the range of furnace models of the European brand Nabertherm for sintering ceramics with maximum operating temperature T_{max} = 1400 °C.

Model	Outer Dimensions (mm)	Inner Dimensions (mm)	Power (kW)	Weight (kg)
Top 60/L	600 × 890 × 850	410 × 410 × 340	29	72
Top 100	660 × 960 × 970	480 × 480 × 570	126	102
Top 140	750 × 1040 × 990	550 × 550 × 570	168	124

Assessments of the energy consumption of various technologies for the sintering of filter ceramics were carried out under the following assumptions [49,50]:

- Each variant of the thermal cycle was considered as a set of stages of heating and high-temperature holding (the cooling stage together with the furnace or outside it was not considered, as either not needing electric power support at all or carried out with a relatively small energy intensity of such support);
- The sequence of stages corresponded to a nondecreasing sequence of values of the heating temperature and high-temperature holding, specified in a certain way by the regulations of the technological process;
- The energy consumption of thermal equipment was proportional to its installed capacity.

The temperature limits of each stage were values within which the heating intensity was maintained constant and equal to a certain value:

$$I_i = \frac{(T_i - T_{i-1})}{\tau i - \tau i - 1}. \tag{1}$$

For the stages of high-temperature holding $T_i = T_{i-1}$ and $I_i = 0$, in addition to I_i, T_i and T_{i-1}, were determined by the characteristics of the stage by the average temperature in the interval $(T_{i-1},\ T_i)$, which we called the equivalent temperature:

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

Assuming, in the general (nonlinear) case, that the equivalence criterion was the fulfillment of equality:

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

where

$$\Delta\tau = \tau(T_i) - \tau(T_{i-1}). \tag{4}$$

According to the second law of thermodynamics, the transfer of heat in a reversible thermal process is proportional to the thermodynamic temperature of the system and the change in its entropy [51]:

$$\delta Q = T \cdot dS. \tag{5}$$

An instantaneous (in an arbitrarily small unit of time) increment of the system's heat capacity by an additional (external) energy-consuming (electric power) effect led to an instantaneous increment of the system temperature corresponding to the instantaneous power of such an additional effect. The resulting identification characteristic of this process with uniform (controlled) heating of the system at some stage of the thermal cycle was a change in the temperature of the system, determined by the intensity and time of heating. Thus, for each stage of the thermal cycle, by analogy with (2) and taking into account the nameplate characteristics of the furnace, which determine the maximum power N_{max} and maximum operating temperature T_{max}, as well as the initial temperature T_0 of the furnace working chamber in the thermal cycle, it was possible to calculate the equivalent power N_{ei}, i.e., its average value, according to [52]:

$$N_{ei} = \frac{T_{ei} - T_0}{T_{max} - T_0} \cdot N_{max}. \tag{6}$$

Approximation (6) allowed to obtain tentative assessments under uncertainty of the characteristic "instantaneous power-instantaneous furnace temperature" at idle (without loading), when solving a priori prognostic (design) tasks related to preliminary analysis and selection of technological solutions. Obviously, in this case, the equivalence criterion was equality [52]:

$$\int_{\tau=\tau(T_{i-1})}^{\tau=\tau(\mathrm{T_i})} N_{(\tau)} d\tau = N_{ei} \cdot \Delta\tau_i, \tag{7}$$

which, at $T_0 = 0\,^\circ\mathrm{C}$ was related to Equation (3) by the proportionality coefficient N_{max}/T_{max}, which was a complex characteristic parameter of the furnace. Equation (7) defined the energy consumption for the implementation of the corresponding stages of the thermal cycle. The energy consumption of the implementation of the thermal cycle as a whole could be found using the following expression [52]:

$$W = \sum_{i=1}^{i=n} N_{ei} \cdot \Delta\tau_i. \tag{8}$$

The furnace power distributed over the hearth area was determined with the following dependence:

$$W_s = N_{max}/S_f. \tag{9}$$

As an indicator to assess the energy efficiency of thermal cycles during the sintering process of the foam ceramic filter, the parameter E_e was proposed, which characterized the effect of the consumed furnace power on the energy efficiency of its operation:

$$E_e = \frac{\sum_{i=1}^{i=n} Nei\Delta\tau i}{\sum_{i=1}^{i=n} Nmax\Delta\tau i}. \tag{10}$$

The relative indicator E_r characterized the simultaneous influence of the sintering temperature and the consumed furnace power on the energy efficiency of the sintering process of foam ceramic filters, and was determined using the proposed equation:

$$E_r = \frac{\sum_{i=1}^{i=n} Tei\Delta\tau i\; Nmax}{\sum_{i=1}^{i=n} Tmax\Delta\tau i\; Nei}. \tag{11}$$

The dependences given above and the proposed indicators (10) and (11) allowed to calculate the power consumption and assess the energy efficiency of the sintering process of foam ceramic materials in a thermal cycle with various manufacturing technologies.

4. Results and Discussion

Figure 1 shows the cyclograms of heating and high-temperature holding in the intensified thermal cycles of the production of aluminum oxide ceramic filters with a porosity of PPI 20.

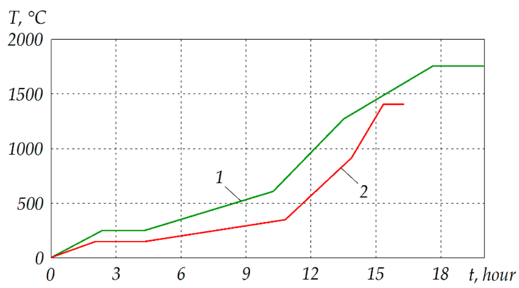

Figure 1. Cyclograms of heating and high-temperature holding in thermal cycles of porous aluminum oxide ceramic technologies without additives of other metal oxides (1) and with two percent additives of titanium and manganese dioxides (2).

From the comparison of the cyclographic characteristics of temperatures and time of the two technologies for the manufacture of porous ceramics presented in Figure 1, it was obvious that the use of sintering technology filters with two percent additives of titanium dioxide and manganese could reduce the required heating temperature and high-temperature holding [53]. As a result (see Figure 1), the completion time of the thermal cycle (16.2 h) and the maximum temperature in the cycle (1350 °C) were 19% and 20% less, respectively, which allowed for the use of less energy-intensive furnace equipment.

Table 4 shows some characteristics of these thermal cycles of intensified technologies, as well as furnaces used in their implementation in pilot laboratory production, including for the well-known technology (with the addition of 13% chromium oxide) proposed by Saggio–Woyansky et al. [5,54]. Table 4 compares the various thermal sintering cycles of porous alumina ceramics, including the thermal cycle using the maximum sintering temperature and power. The accuracy of the temperature measurement corresponded to the technical characteristics of the furnaces used. According to these operational characteristics and the accepted model, using dependences (2), (5) and (6), respectively, the values of T_{ei}, N_{ei} and W_i were obtained for the stages of heating and high-temperature holding of each of the technologies. The value of the initial heating temperature of the furnace in the considered cases was set at $T_0 = 20$ °C.

Table 4. Energy consumption in the thermal cycle of various manufacturing technologies of porous aluminum oxide ceramics in real conditions of experimental laboratory production.

Technology	Characteristics of Furnace		Characteristics of Technology Stages	Sequence of Stages of Heating and High-Temperature Holding					
	T_{max} (°C)	N_{max} (kW)		I	II	III	IV	V	VI
Typical with additive 13% Cr_2O_3	1400	2.5	Duration of the stage (h)	1.75	1.0	12.5	1.0	14.15	5.0
			Average temperature (°C)	72.5	125	312.5	500	925	1350
			Average power (kW)	0.10	0.19	0.53	0.87	1.64	2.41
			Energy consumption (kW h)	0.17	0.19	6.62	0.87	23.2	12.05
Intensified without metal oxide additives	2500	35	Duration of the stage (h)	2.3	2.0	5.8	3.25	4.15	2.5
			Average temperature (°C)	135	250	425	925	1500	1750
			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 additives 2% TiO_2 + 2% MnO_2	1400	2.5	Duration of the stage (h)	2.15	2.0	6.65	3.05	1. 35	1.0
			Average temperature (°C)	85	150	250	625	1150	1400
			Average power (kW)	0.12	0.24	0.42	1.10	2.05	2.50
			Energy consumption (kW h)	0.25	0.47	2.77	3.34	2.76	2.50

It should be noted that Figure 2 shows an assessment of the ratio of the duration of the technological cycle and power consumption when using two different compositions of ceramics; the figure on the left side shows the real ratio between the full power of the furnace and the actually used, in terms of sintering time, and the figure on the right side is similar to the ratio of power consumption.

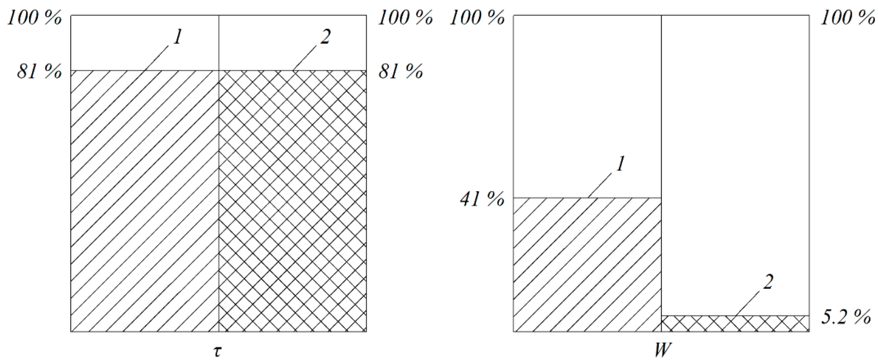

Figure 2. The relative duration (τ) and energy intensity (W) of heating and high-temperature holding in the thermal cycle of the manufacture of aluminum oxide ceramics without additives of other metal oxides (100%) and with two percent additives of titanium and manganese dioxides in equivalent (1) and real (2) conditions of experimental laboratory production.

The total energy savings when using a polyoxide technological alternative were up to 40% under comparable technical experimental and laboratory conditions (furnace parameters: N_{max} = 35 kW; T_{max} = 2500 °C) and 5.2%—under conditions of sintering aluminum oxide ceramics using titanium dioxide and manganese additives in a furnace with N_{max} = 2.5 kW and T_{max} = 1400 °C.

The discrepancy in the estimates of energy consumption during the implementation of cyclograms (see Figure 2) for mono- and polyoxide ceramics in terms of maximum and equivalent power were be determined with the N_{max}/N_e ratio, and at $T_0 = 20$ °C was more than 200% for the evaluation of monoxide technology (200.9%), as well as for the evaluation of polyoxide technology (233.3%). Thus, it was obvious that the use of the proposed model for assessing the energy efficiency of selected technologies for sintering porous ceramics in forecasting and analyzing the indicators of the thermal cycle could significantly increase the reliability of the expert assessments performed.

It should be noted that based on the data in Table 4 and the proposed model to assess the energy efficiency of technologies, it was possible to obtain the following quantitative characteristics of the advantages of the technology of intensified aluminum oxide ceramics using 2% additives of titanium and manganese dioxide compared to a similar technology with the addition of 13% chromium oxide ($T_0 = 20$ °C): in terms of productivity (without considering the cooling stage)—more than 2 times (with the duration of the stages of heating and high-temperature holding, respectively, 16.2 h and 35.4 h); in terms of energy consumption—more than 3.5 times (12.1 kW h and 43.1 kW h, respectively).

Let us focus on two issues, the impact of which is less significant on the final technical and economic results of production, but which should also be taken into account in the process of managing the production of porous ceramics. The first question is related to the effect of the initial temperature T_0 on the production efficiency of porous ceramics, and the second question is related to the cooling stage.

As follows, from Table 5, lowering the initial temperature of the thermal cycle from 40 °C to 20 °C in each of the considered technological options gave a decrease in the lower limit of the thermal cycle with an extension of its temperature range by 1.2% for technology without metal oxide additives and by 1.5% for technology with two percent additives of titanium and manganese dioxides. The use of the residual heat of the furnace helps to reduce the time of the thermal cycle of production and, accordingly, the level of energy consumption.

Table 5. General characteristics of thermal cycles at different values of their initial temperature.

Technology	Furnace Characteristics		Initial Temperature T_0 (°C)	Estimated Estimates			
	T_{max} (°C)	N_{max} (kW)		T_e (°C)	N_{max} (kW)	W (kW h)	$\sum \Delta\tau_0$, (h)
Intensified without metal oxide additives	2500	35	20 40	835.8 844.1	11.70 11.63	236.37 232.61	20.2 20.0
Intensified with additives 2% TiO_2 + 2% MnO_2	1400	2.5	20 40	423.5 432.3	0.76 0.75	12.52 12.10	16.55 16.2

According to Figure 3, the reduction in the heating time $\Delta\tau_0$ at the first stage of the thermal cycle by increasing its initial temperature by the value ΔT_0 at a given heating intensity I_1 was determined from the following ratio:

$$\Delta\tau_0 = \frac{\Delta T_0}{I_1}. \quad (12)$$

The cooling stage was not considered in detail by us, since it is not energy-intensive: the 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/min) [6]. Figure 3 shows the dependencies according to Equation (3). The heating intensity of the furnace was estimated with Equation (1).

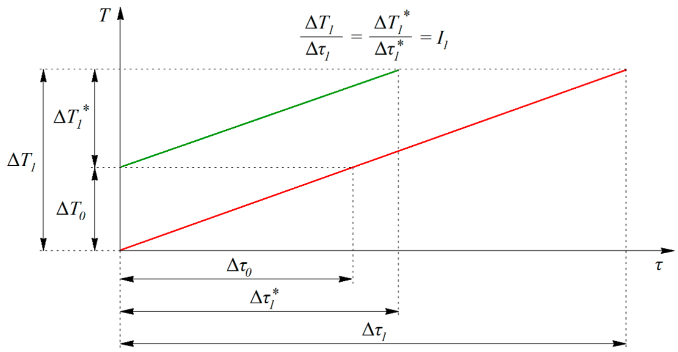

Figure 3. Dependence of the first heating stage in variations of the initial temperature (T_0* > T_0) at a given heating intensity (I_1 = const).

The deceleration of the furnace cooling by a gradual decrease in electrical power is usually not required [53]. It was possible to reduce the auxiliary time for loading and unloading operations the furnace in the full working cycle of ceramic production using furnaces of the European brand Nabertherm (Table 3). The furnaces used more effectively drew-out the residual heat. However, the facility of such furnaces in the buildings of CMFMCs is not always possible due to their large overall dimensions and the limited capabilities of freight elevators, although their use is not excluded with the modular design of such furnaces.

The reduction in the amount of unproductive operating time of the furnace is ensured by the fact that, for each furnace, two hearths are simultaneously involved: 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, using a bogie system practically means no downtime of the furnace. This mechanism of using the bogie hearth system, thanks to the reduction in the time for loading and unloading the furnace, also makes it possible to use the residual heat to a greater extent, which is especially evident when operating large furnaces with a full load.

The change in the hearth area slightly affected the value of W_s, which characterized the distribution of the furnace power over the hearth area. For example, with a twofold increase in the hearth area in the presented model LCF 12/560 (S_f = 2.8 m^2) of Nabertherm furnaces, the value of W_s changed to 10% (Figure 4). Therefore, with a single-tier loading of the furnace, a more complete use of the hearth area had little effect on the energy consumption per unit of sintered products.

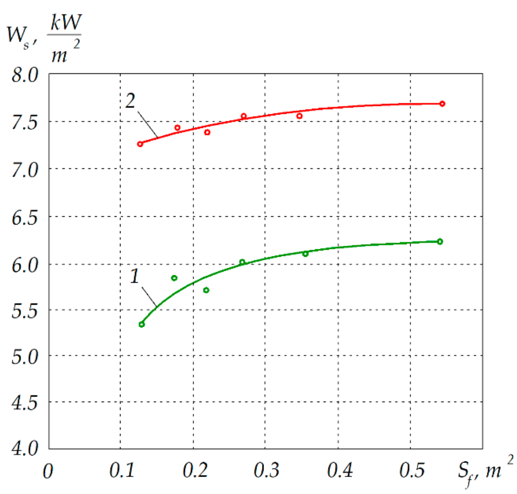

Figure 4. The dependences of power W_s distributed on the hearth area S_f for a range of models of Nabertherm furnaces designed for sintering ceramics with maximum operating temperatures: 1—T_{max} = 1400 °C; 2—T_{max} = 1600 °C.

The furnace temperature of 1600 °C uses completely different heaters, which are much more expensive and have a lower life span. In this case, this temperature was given for comparison purposes.

It follows on that the reduction in energy consumption during sintering could be achieved by using more expensive bogie hearth furnaces with larger overall dimensions and weights, which, in some cases, cannot be installed in CMFMC buildings due to the limited capabilities of their freight elevators. From the consumer's point of view, the economic feasibility of using such progressive, but expensive, equipment arises with sufficiently large volumes of orders and a steady demand. In addition, with the use of equipment of increased complexity, additional issues arise of reserving the reliability of the technological systems that include it, the solution of which is also associated with additional costs that can only be justified in serial and mass production.

The relatively high level of power distributed over the hearth area W_s when using furnaces with a movable hearth without additional upper burners compared to conventional tunnel furnaces was compensated by the possibility of more efficient use of residual heat, a reduction in auxiliary time for loading and unloading operations and high quality of the products obtained (Table 6). All four parameters shown in Table 6 depended on the sintering temperature and energy savings. It was obvious that in the conditions of serial and mass production, the most effective solution seemed to be the use of furnaces with a movable hearth without additional upper burners.

Table 6. Comparative qualitative characteristics of foam ceramic filters manufactured using aluminum oxide ceramics technology without additives of other metal oxides (100%) and energy-saving technology with two percent additives of titanium and manganese dioxides.

Technology	**Characteristics**			
	Density (g/cm^3)	**Flexural Strength (MPa)**	**Porosity (%)**	**Air Permeability (nPa)**
Intensified without metal oxide additives	1.20	10.5	63	200
Intensified with additives 2%TiO_2 + 2% MnO_2	1.35	25	70	250

Figure 5 clearly shows that by changing the indicator E_e, the equivalent power of the furnace changed when sintering different compositions of ceramic filters. Such a significant difference is explained by a general decrease in temperature and a reduction in the overall sintering cycle due to the use of submicron additives to aluminum oxide. Obviously, in the case of using nanodispersed additives, this difference would increase even more due to the activation of the sintering process, and, consequently, an additional decrease in temperature.

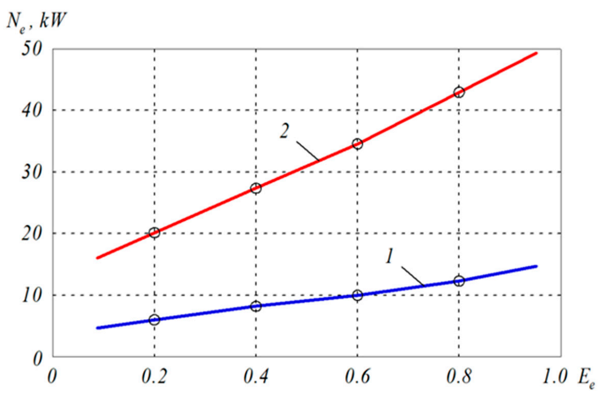

Figure 5. The dependence of the equivalent power on indicator E_e during sintering of aluminum oxide ceramics with two percent additives of titanium and manganese dioxides (1) and without additives of other metal oxides (2).

Figure 6 shows the dependence of the energy consumption of an electric furnace on the relative indicator E_r for two types of technologies for producing foam ceramic filters. The peculiarity of the relative indicator E_r was that it took into account the influence of two parameters of temperature and equivalent power at once.

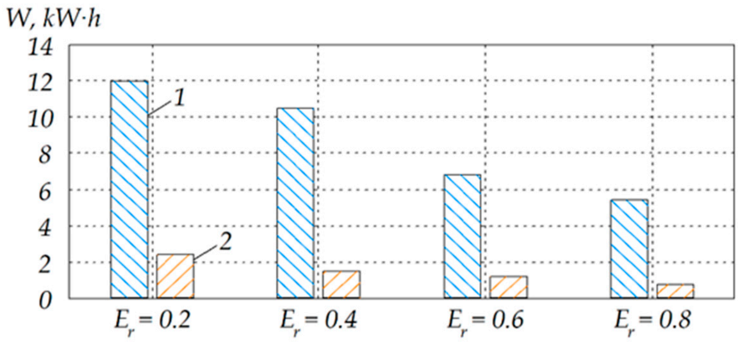

Figure 6. The dependence of the energy consumption W of the furnace in the manufacture of ceramic filters on relative indicator E_r: 1—aluminum oxide without additives; 2—aluminum oxide with metal oxide additives.

The data on the diagram were obtained using Equations (10) and (11), and were relative indicators of energy consumption during filter sintering. The relative indicator characterized the simultaneous influence of the sintering temperature and the consumed furnace power on the energy efficiency of the sintering process of foam ceramic filters.

5. Managerial Implications

The high-energy intensity of the sintering process of foam composite filters with limited energy consumption in CMFMCs had a greater impact on decision making on the choice of the technological process of manufacture. Below are recommendations for operators/managers for the production of foam composite filters on the choice of energy-efficient technologies and appropriate equipment for their use within the framework of a smart sustainable CMFMC:

- This research could help managers in organizing the production of foam ceramic filters within CMFMCs, providing the smart management of production and supply chains in real time and avoiding negative economic, social and environmental consequences [1,3–5]. At the same time, this paper focused on issues related to decision making on energy reduction at the stage of choosing the technology and equipment for the production of foam ceramic filters.
- The main purpose of this study was to develop the model and indicators to assess the energy efficiency of the choice of foam ceramic filter sintering technology, which are necessary tools for making managerial production and technological decisions within the framework of smart sustainable CMFMCs.
- The choice of technological equipment is also related to the possibility of their delivery and placement on the appropriate production floors of CMFMC buildings. The overall dimensions and weight of the technological equipment must satisfy the capabilities of the freight elevators the CMFMC buildings [1,3,27]. The use of large-sized technological equipment is possible only in a modular design with the possibility of modular delivery to production facilities, as well as a frame, lightweight design [25,26]. At the same time, it should be borne in mind that furnaces with large dimensions of working chambers for the implementation of thermal sintering processes and, consequently, large overall dimensions are more productive due to the simultaneous manufacture of a larger number of products.

- The assessment of technologies, the choice of technological equipment and its placement in the cluster's manufacturing building should be carried out considering the residual capabilities of its electrical network and the planned electricity costs for production needs for a certain period of time.
- The choice of sintering technology for foam ceramic filters is based on the proposed model and indicators for assessing the energy efficiency of the manufacturing process. In addition, when choosing a technology for sintering foam ceramic filters, the dimensions of products and production volumes are considered. Realtime production planning should consider the residual capacity of the electrical network of each manufacturing building of the cluster.
- The planning of operational and long-term schedules of electricity consumption by manufacturing enterprises in cases of using energy-intensive technological equipment in CMFMC buildings helps to prevent peak overloads of the electrical grid.
- The uniform distribution of energy-intensive technological equipment between the manufacturing buildings of the cluster and its alternation with less energy-intensive technological processes and equipment at enterprises helps to reduce peak loads in the electrical grid due to the uniform redistribution of orders during the operational planning of the manufacture of energy-intensive products.
- The use of a daily time fund with the lowest electricity tariffs for energy-intensive production and alternative renewable energy sources.
- It should be noted that the high energy consumption for the process under consideration imposes the need for high-power medium voltage power lines. The action of such lines on building structures, especially those of steel or reinforced concrete construction, under the conditions of industrial environments may result in the development of corrosion or degradation processes. The important role of capacitive currents was indicated, as well as the role of stray currents generated as a result of asymmetrical loading of phases. Long-term exposure of facilities to such activities can, in turn, threaten their structural integrity [55].
- The organization of production using high-temperature furnaces within the framework of CMFMCs was carried out on the basis of international standards, among which the following could be distinguished: ISO 50001:2018 Energy management systems—Requirements with guidance for use; ISO 23932-1:2018 Fire safety engineering; ISO 14006:2020 Environmental management systems—Guidelines for incorporating ecodesign; ISO 16890:2016 Air filters for general ventilation; ISO 45001:2018 Occupational health and safety management systems—Requirements with guidance for use [56].

The proposed structure covered a detailed range of issues related to the organization and management of the production of foam composite filters within smart sustainable CMFMCs. Information support for determining energy-saving decisions in the short- and long-term can contribute to effective production planning, increase its productivity and flexibility and rational use of CMFMC capabilities from the point of view of economic, social and environmental aspects. Such information is useful for production operators/managers within smart sustainable CMFMCs to offer or propose the best management solutions aimed at improving the energy efficiency of using the potential of the cluster's production enterprises.

6. Conclusions

This paper discussed the specific issues of using energy-intensive industries within CMFMCs on the example of the production of ceramic foam filters using high-temperature furnaces. This was conducted due to the sustainable approach for the use of energy-intensive industries and technologies within CMFMCs and the presence of restrictions on the overall dimensions of furnaces and their weight, determined by the capabilities of freight elevators in the manufacturing building of clusters. The conducted study showed:

- The need to improve sintering technologies to obtain products with the necessary physical and mechanical properties at lower temperatures;
- The possibility of organizing the production of various ceramic products within smart and sustainable CMFMCs considering the established restrictions on power consumption, overall dimensions and weight of the furnaces used.

In this study, the possibility of improving the energy efficiency of manufacturing porous permeable aluminum oxide ceramics without reducing the productivity of production within the CMFMC was investigated. The implementation of comparative estimates of energy intensity and fundamental technological polyvariants and the technical medium of their possible implementation was based on the proposed model and indicators to assess the energy efficiency of the choice of foam ceramic filter sintering technology for smart sustainable production management within CMFMCs. The conducted study showed that the use of proposed indicators to assess the energy efficiency of the sintering technology of foam ceramic filters reduced the completion time of the heating cycle and high-temperature holding by 19%, and the maximum temperature was reduced by 20% to 1350 °C, which allowed for the use of simpler and less energy-intensive equipment in conditions of existing power consumption limitations of CMFMCs. Improving the technology of sintering ceramic foam filters by adopting a different oxide alternative and using the proposed model for assessing the energy efficiency of production allowed for it to be possible to choose less energy-intensive equipment and save up to 40% in electricity.

The high-energy intensity of the sintering process of foam composite filters under the limitation energy consumption in the CMFMCs put more pressure on decision making on choosing the most energy-efficient technological process for their production. Recommendations were given for operators/managers of the production of foam composite filters on the choice of energy-efficient technologies and equipment.

The immediate prospect of the further development of ceramic filter manufacturing technology is associated with the search for new additives to reduce energy consumption in the sintering process and the study of energy consumption issues at individual stages of the sintering process from the point of view of minimizing the power consumption. These studies can be the basis for the search for alternative and less expensive technologies for the manufacture of ceramic filters, in particular powder metallurgies, for their more efficient use within CMFMCs.

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Nomenclature

Indexes

I	Number of stages in the thermal cycle of heating and high-temperature holding in the sintering process of the foam ceramic filter, $i = 1, 2, 3, \ldots, n$.

Parameters

τ_i	Heating time of item i (h);
I_i	Heating intensity of item i (°C/h);
T_i	Temperature of the high-temperature holding stage of item i (°C);
τ	Current time (h);
Q	Heat during reversible thermal processes of the system (kJ);
T	Temperature of the system (°C);
S	Entropy of the system (kJ/°C);
T_{ei}	Equivalent temperature of item i (°C);
N_{ei}	Equivalent power of item i (kW);
N_{max}	Maximum power during sintering process (kW);
T_{max}	Maximum temperature during sintering process (°C);
N_{max}/T_{max}	Proportionality factor (kW/°C);
T_0	Initial temperature of furnace (°C);
ΔT_0	Increasing the initial temperature of furnace (°C);
$\Delta\tau_0$	Reduction in heating time (h);
W	Energy consumption (kW h);
E_e	Indicator to assess the energy efficiency of thermal cycles during sintering process of the foam ceramic filter;
E_r	Relative indicator to assess the energy efficiency of thermal cycles during sintering process of the foam ceramic filter;
S_f	Furnace hearth area (m^2);
W_s	Power distributed over the hearth area (kW/m^2).

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