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RESEARCH INTO THE IMPACT OF STRUCTURAL FEATURES OF COMBUSTION CHAMBER IN ENERGY-TECHNOLOGICAL UNITS ON THEIR OPERATIONAL EFFICIENCY

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Виконано експериментальні дослідження впливу ступеня розвитку кладки (геометрії) і аеродинаміки топкових камер (схеми евакуації продуктів згоряння) на енерготехнологічні показники процесів в системі газ-тверде тіло (в топкових камерах). На промисловому великомасштабному вогневому стенді проведені експериментальні дослідження впливу геометрії і аеродинаміки топкової камери на енерготехнологічні показники в системі газ-тверде тіло.

Показано, що зменшення висоти робочого простору камери згоряння, обладнаної плоскополум'яних пальниками, впливає на паливовикористання за рахунок інтенсифікації теплообміну, в тому числі прямій конвекції. Залежність обумовлена зменшення втрат тепла з вихідними газами, а також за рахунок зменшення втрат теплоти через кладку.

Встановлено, що при висоті робочого простору 800÷1000 мм камери згоряння з плоскополум'яними пальниками відбувається скорочення витрат палива на 20÷30 %.

Розроблено конструкцію топкового простору печі безперервного режиму роботи. Відмінною особливістю печі розробленої конструкції є ліквідація дискретності і реалізація стабільного безперервного режиму роботи теплоагрегату. На бічних поверхнях вагонеток і печі були виконані по всій довжині канали, що дозволяє реалізувати безперервний відбір продуктів згоряння з пічного простору через каналізований під вагонеток. При будь-якій швидкості переміщення вагонеток забезпечується додаткове аеродинамічний ущільнення робочого простору печі.

Енерготехнологічна ефективність при сводовому опаленні паливних агрегатів з плоскополум'яними пальниками і евакуацією продуктів згоряння під заготівлею вище в середньому в 1,3 рази, ніж при бічному димовидаленні в діючих печах.

Розроблено конструкцію і пущена в експлуатацію тунельна піч для хіміко-термічної обробки металевих і неметалевих матеріалів і виробів при їх нагріванні за заданим графіком

Ключові слова: топкова камера, аеродинаміка, плоскополум'яних пальник, тунельна піч, температура продуктів згоряння

1. Introduction

The technical level of the operating and newly created energy-technological units for chemical industries does not always meet modern requirements for ecology, energy efficiency and ensuring proper quality of the parameters demanded by technology. Only a small amount of modern technological equipment of chemical industry is based on the use of energy efficient synergetic reactive mass exchange processes [1].

The experimental research aimed at creating highly effective energy-technological units and systems that meet modern requirements of chemical enterprises should be considered relevant.

The basis for modern tendencies of designing and construction of highly effective energy-technological systems and equipment is the unit-modular principle [2]. Its essence is the unity of the methods of apparatus-structural (AS) and mode-technological (MT) organization of the process [3]. In this case, there is no clear boundary between the methods. The MT methods are a set of techniques for intensification of heat and mass exchange processes, each of which can be used in a particular case. In practice, the use of the MT method when designing technological equipment involves certain structural changes and using the AS methods.

2. Literature review and problem statement

In the modern industry, the problem of choosing an efficient heating system of combustion chambers of energy-technological units for chemical production in the face of a wide range of proposed technologies and thermal engineering equipment is weakly structured and highly relevant [4, 5]. This is due to the lack of a common approach to the assessment of effectiveness of energy-technological units and direct methods of control over effectiveness parameters.

The main part of the thermal system of the combustion chamber of an energy-technological unit is a heat generation source – a burner device (a burner), an electric generator. A flat flame burner, developed at the Institute of Gas of the NAS of Ukraine, is a specific device, which makes it possible to organize an open torch (opening angle is 180 °C). The phenomenon of breaking the torch is the organization of the Coandă effect, the nature of which is determined by the existence of the pressure gradient across the asymmetric flow with gas leaks to the jet from the side of the surfaces, limiting the operation space.

Along with high aerodynamic perfection, the design of the burner ensured a wide range of steady operation in the open flame mode in the range of 1:10. In this case, the nominal gas pressure is in the range of 3–70 kN/m^2, the composition of flue products of gas combustion is characterized by the low content of NO_x at the level of 50–70 mg/m^3 in flue gases [7].

The listed merits of flat flame burners testify to the convincing prospects of their use as the AS method of designing MT process of heating materials in the thermal technological units. Flat flame burners have already been successfully used in several thermal devices, such as: composite type reactors [7], devices of submersible burning (DSB) [8], refractory chambers, plants of thermal disposal of liquid toxic wastes [9].

Papers [7, 8] show the influence of the structural circuit of the design of the combustion space of the furnace on power efficiency of the process and its technological parameters (uniformity of a temperature field) on the proposed mass exchange models, taking into consideration the aerodynamics of a combustion chamber. Aerodynamics of a combustion chamber with strengthening the heat and mass transfer component and the arrangement of the burners are so great that it determines integral heat transfer and power efficiency of technological process in general [10, 11].

Article [12] describes the design of the combustion chamber with a jet burner. However, this furnace can only be used under laboratory conditions and the use in the chemical technology requires significant changes in the design.

The authors of [13, 14] studied the efficiency of a combustion chamber when using different types of fuel: methane, hydrogen and gas mixtures in various concentrations. In paper [15], the mathematical model of the kinetic mechanism of combustion in the operating chamber was explored. Paper [14] also takes into consideration the geometry of the combustion chamber, but the authors do not provide the data on the structure of real energy-technological units.

In study [16], with the use of 3D-modeling based on the solution of differential equations of turbulent reactive streams, the dependences of the velocity vector on the height of the combustion chamber, temperature profiles and their distribution at the height of the combustion chamber were obtained.

Paper [17] deals with modeling the combustion chamber of the industrial unit, however, the study has theoretical character and does not contain any recommendations for practical implementation or design of a thermal-technical unit.

Despite a great variety of studies [7–17], related to the exploration of combustion chambers, the papers are theoretical in nature and focus on highly specialized industry (heating equipment, production of silicate materials, etc.). The data, technical proposals, structures of highly efficient combustion chambers for energy-technological units with the possibility of their using in various chemical technologies were not found. The lack of such information forces professionals to find non-standard solutions to design problems in every specific case. The consequence of such an approach during designing energy-technological units is their excessive structural complexity.

Thus, development of highly efficient design of a combustion chamber for energy-technological units of chemical technology is a promising aspect of the implementation of modern power-efficient technologies in the industry.

3. The aim and objectives of the study

The aim of the present research is to develop and research a high-performance design of a combustion chamber in terms of ensuring precise heating of the treated material at minimum fuel consumption for energy-technological units of chemical technology.

To achieve the set aim, the following tasks have been solved:

– under conditions of unilateral fuel input using an arch flat flame burner, to explore the influence of the mutual orientation of the receiver and masonry (combustion space aerodynamics), the degree of development of masonry (geometry of combustion space) on energy-technical characteristics;

– to determine the optimal geometry of the operation space of a combustion chamber;

– based on the obtained experimental data, to develop recommendations on apparatus-structural design of the combustion space of energy-technological units and integrate the research results in the design of energy-technological units for chemical and thermal treatment of metallic and non-metallic materials.

4. Description of experimental research into a fire bench

4. 1. Research into aerodynamics of the combustion chamber in a fire bench

Solution of the problems in line with the set goals was carried out with the help of a large-scale fire bench. Under industrial conditions, we constructed a large-scale fire bench with the dimensions of the working space $B \times L$ 1,500×1,500 mm with the changing geometry (the height of the workspace) and aerodynamics (the circuit of removal of combustion products from the combustion space). The height of the operation space was varied with the help of a removable arch with a built-in flat fire burner TPPC-4 with performance of 40 m^3/h of natural gas, which was mounted at the selected level. The circuit of evacuation of combustion products from the combustion space was changed by the lines of combustion products flowing with the help of the specially made channels in the hearth and the side walls of the combustion space (Fig. 1).

The accepted location of the channels in combination with heating by a flat flame burner made it possible to create different schemes of motions of combustion products in the workspace.

At heating the material and the evacuation of combustion products through the channels in the central part of the hearth, the bilateral heating of a product at the unilateral fuel introduction is implemented (Fig. 1, *a*).

The unilateral heating is implemented by removal of combustion products through the channels in the side walls of the combustion space (Fig. 1, *b*). In this case, a refractory wall, preventing the gas motion under material, was built from the hearth to the heated sheet on the perimeter of the latter.

The product during heating was a sheet of steel St3 of dimensions of 1,500×1,270×30 mm and weight of 0.449 t. Chromel-alumel thermocouples 1–5 (Fig. 2) were mounted on the surfaces of the sheet at the depth of 5–7 mm.

To decrease the measurement errors, associated with waste of metal and change in its thickness, two identical sheets of metal were alternately used in the study.

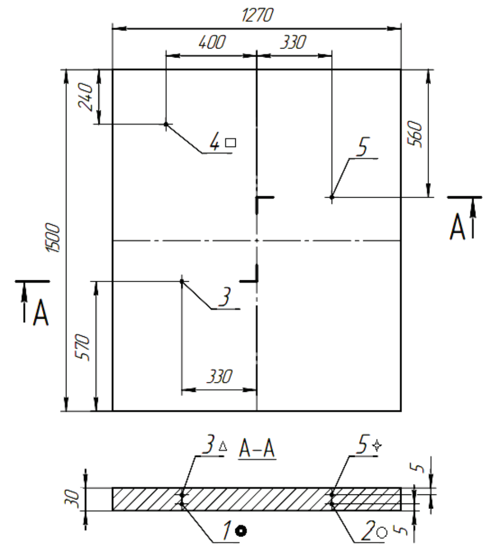

Fig. 2. Schematic of location and conditional thermocouples on the control sheet workpiece

In order to maintain the constant of blackness degree of the heated sheet in experimental heating, especially in the initial period, the surface of the product was covered on both sides with the special suspension of the following composition (in weight part) [7]:

– water – 100;

– soot technical DF-100-10-15;

– oxyethylized alkyl-phenol – 0.01.

Suspension of such composition makes it possible to obtain the maximum blackness degree $\varepsilon=0.95$ and good wetting with the surface of the heated product [7].

The constancy of blackness degree of the internal surface of the working chamber in the control experiments was ensured by burning natural gas with excess oxidizer coefficient $\alpha=0.8$, in this case, the temperature in the working space reached the value of 1,273 K.

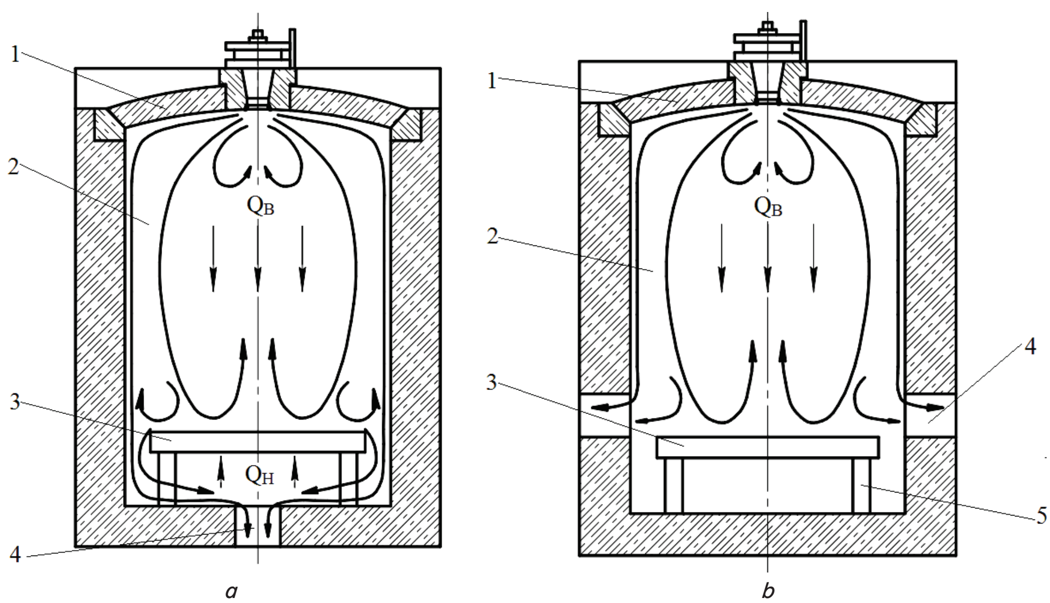

Fig. 1. The lines of the combustion products flow in the workspace of the experimental bench: *a* – evacuation of combustion products through the channels in the central part of the feed with organization of bilateral heating; *b* – evacuation of combustion products through the lateral channels with organization of unilateral heating: 1 – removable input with a flat flame burner; 2 – furnace space; 3 – heated product; 4 – channels; 5 – refractory wall

In the experiments, the heated product was introduced into the workspace of the bench after reaching inside its stationary thermal state.

All the experiments were carried out at gas flow to the bench of 43 $m^3/h = idem \neq f(\tau)$.

In the course of studying, the temperatures of the surface of the masonry of the upper and lower zones of workspace at the height of 200 and 900 mm from the arch were controlled with the help of chromel-alumel thermocouples.

The temperature of combustion products at the surface of the heated metal, as well as underneath, was controlled using the vibration-rod temperature converters [18]. The temperature control system of the working space included 16 control points, 5 of which ensure the control of uniformity of heating the surface of material. Other control points of the temperature field in a volume of the combustion space make it possible to implement the control of temperature of combustion products throughout the whole volume of the working space of the bench (near the arch and on its lateral surfaces directly above and below the heated product). Data filtering was implemented programmatically using the Kalman adaptive filter [19].

Gas flow to the bench was controlled by the gas flow meter RG-40 and the rotameter RMF-V1 by standard techniques.

Natural gas and combustion products were analyzed in order to maintain equal air surplus in compared experiments. The analysis of combustion products was performed on the portable chromatographer «Gazochrom «Soyuz-3101» (Russia) and the gas analyzer «Testo-34» (Germany).

The composition of natural gas was controlled using the chromatograph LHN-72. In the control experiments, the heat of natural gas combustion remained on average at the level of 37.2 MJ/m^3, the gas flow was maintained equal to 43 m^3/h, air excess air coefficient $\alpha = 1.05 \div 1.1$. In each experiment, thermal losses through the masonry of the arch and the walls were measured using device ETP-6.

We selected the parameters as the criteria for evaluation of the energy-technological effectiveness of the design of the combustion chamber, which characterize:

– intensity and power efficiency of heating: heating rate (a differential value), duration of heating to the fixed temperature (an integral value) of the workpiece along the thickness and the value of the energy efficiency of heating;

– quality of heating: uniformity of temperature field on the surface and the thickness of the workpiece during and at the end of the heating process.

In a series of the conducted experiments, the same height of the working space was set in each thermocouple, the scheme of the evacuation of combustion products was changed (Table 1).

Table 1

Averaged indicators of heating duration at various circuits of smoke removal in the variable range of studied heights

No. of experiment	Height of working space, H, mm	Smoke removal	Implemented heating	Heating duration τ, min	Relative reduction of heating duration, Δτ, %
1	1,500	Lower	Bilateral	31	24.4
2	1,500	Lateral	Unilateral	41	
3	1,150	Lower	Bilateral	23	23.4
4	1,150	Lateral	Unilateral	30	
5	800	Lower	Bilateral	21	22.2
6	800	Lateral	Unilateral	27	

Table 1 shows the averaged results of research, from which it follows:

– heating rate in the variable range of heights of 800–1,500 mm at lower smoke evacuation (bilateral heating, Fig. 1, *a*) is higher than at the lateral smoke evacuation (unilateral heating, Fig. 1, *b*);

– the heat exchange intensity increases with a decrease in the height of the working space, that is, with a decrease in the degree of development of masonry in the variable range of the studied heights.

Relative reduction of heating duration (in relation of the time of bilateral heating to the time of unilateral heating) in the studied range of heights of 800–500 mm is attributable to the increased total thermal flow, falling on the receiver from the top of warmed-up surfaces of the arch and the side walls, as well as from the lower surfaces of the hearth. During the combustion products motion in the direction of the smoke removal channels, located in the hearth (Fig. 1, *a*), the surface of the latter heats up and becomes a source of radiation. In addition, the role of convective component of heat transfer increases.

In this case, the temperature, recorded by the suction thermocouple mounted under the heated metal is in all experiments close to the gas temperature above the surface of the heated metal and differs from it by an average of 25–50 K (Fig. 3). In this case, the absolute level of the temperatures of combustion products noticeably decreases. This suggests an increase in the degree of heat transfer from the gas to the product, which characterizes the intensive heat exchange.

At the lateral smoke removal, metal takes the heat flow, falling only form above of the heated surfaces of the arch and the side walls. Difference in the temperatures of combustion products $\Delta T = T' - T''$ above and below the metal, recorded in this case, reaches 80–115 K. Absolute values of temperatures of flue combustion products in these experiments exceeded those at bilateral heating on average by 40–75 K.

Fig. 3 shows selectively the thermograms of heating and changes over time of the main characteristics (heating rates $dT/d\tau$, temperature differences across the section of the sheet and on its surface), calculated by them for two cases that are the limits by heating duration (experiments 2 and 5).

The thermogram of control heating in experiments 2 and 5 (Fig. 3) shows that after the end of the initial moment after loading the metal, some parts of heating can be approximated by the regular mode of second kind. The mode is characterized by continuity over time of heating rate of any point and the metal sheet $dT/d\tau = \text{const}$. It can be argued that the specified rate is constant not only at the final time sections, but also in the cross section of the sheet $dT_n/d\tau = dT_c/d\tau = dT_i/d\tau$, where indices *n* and *c* refer to the upper surface and the middle of the sheet, respectively.

It is known that the mode that meets these conditions can be set at:

$$F_0 = \frac{\alpha\tau}{x^2} \geq 0.25.$$

In the appropriate time sections, it is possible to consider that heating occurs at the constant heat flow. In this case, the temperature distribution on the cross section of the sheet obeys the law of parabola of second order.

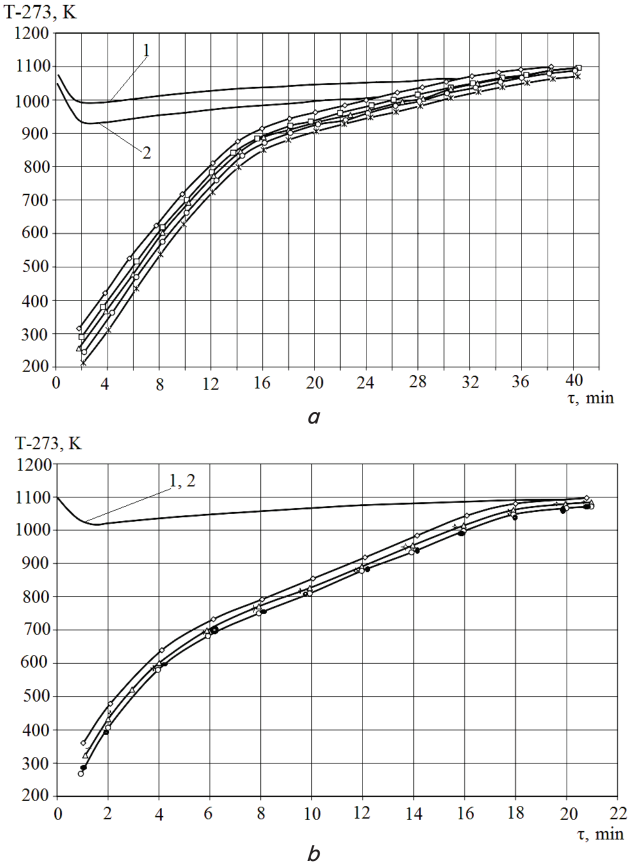

Fig. 3. Thermograms of heating the sheet workpiece: *a* – in experiments 2; *b* – in experiments 5 (designation of points in Fig. 2); 1, 2 – temperature of working space of the upper and lower zones, respectively

Comparison of uniformity of the heat duct across the width of the sheet shows that in all cases the points, located closer to the edge of the sheet (points 4, 5), were heated more quickly than the point, located closer to the loading-unloading window (point 3) (Fig. 2). This is due to increased heat losses in the direction of the loading-unloading window.

Maximum non-uniformity of heating around the entire perimeter of the workpiece during all control heating did not exceed 5–10 K. At the end of the heating period, non-uniformity of the heat feeder in width virtually disappears in all experiments.

4. 2. Determining the optimal geometry of the workspace of the combustion chamber

A decrease in the height of the workspace from 1,500 to 1,150 mm has virtually no effect on non-uniformity of heating on the surface, deviations are ±5 K. With the change of the height from 1,150 to 800 mm during the initial period of heating, non-uniformity on the surface decreases by 15–20 K, by the end of the heating period, non-uniformity disappears regardless of the height.

Thus, the circuit of smoke removal and the height of the working space in general do not influence the heating uniformity on the sheet surface.

A comparative analysis of energy efficiency was performed based on the calculation of heat balances for all control experiments:

$$\eta = \frac{Q_{us}}{BQ_H^P},$$

where Q_{us} is the useful heat taking, a change of enthalpy in the process of heating; B is the fuel consumption; Q_H^P is the heat of fuel combustion. Since the initial (308 K) and final (1.358 K) temperatures of heating in the experiments are the same and temperature differences across the width of the list is practically absent, such comparison can be considered correct for the evaluation of fuel usage efficiency.

Tables 2, 3 shows the results of calculation of the articles of thermal balance and energy efficiency of the experimental heating.

Table 2

Results of calculation of articles of thermal balance and energy efficiency of experimental heating. Credit

No. of experiment	Credit					
	Chemical heat of the fuel Q_{chem}		Oxidation heat Q_{ex}		$Q_{chem}+Q_{ex}$	
	kW	%	kW	%	kW	%
1	444.3	96.8	14.8	3.2	469.1	100
2	444.3	96.6	15.8	3.4	460.1	100
3	444.3	97.1	13.3	2.9	457.6	100
4	444.3	96.8	14.6	3.2	458.9	100
5	444.3	97.2	12.6	2.8	456.9	100
6	444.3	97.0	14.0	3.0	458.3	100

Table 3

Results of calculation of articles of thermal balance and energy efficiency of experimental heating. Debit

No. of experiment	Debit												Efficiency, %
	Useful heat Q_{us}		Losses through masonry Q_m		Losses with flue gases Q_{gas}		Losses with radiation Q_{rad}		Discrepancy Q_{dic}		$Q_{us}+Q_m+$ $+Q_{gas}+Q_{rad}+$ $+Q_{dis}$		
	kW	%	kW	%	kW	%	kW	%	kW	%	kW	%	
1	178	38.8	42.4	9.2	198	43.1	22.1	4.8	18.6	4.1	459.1	100	40.1
2	136	29.6	45.1	9.8	227	49.3	28.8	6.3	23.2	5.0	460.1	100	30.6
3	244	53.3	27.1	5.9	195	42.6	7.4	1.6	–15.9	–3.4	457.6	100	54.9
4	185.3	40.4	29.8	6.5	219.3	47.8	8.6	1.9	15.9	3.4	458.9	100	41.7
5	265	58.0	20.1	4.4	183	40.0	5.9	1.3	–17.1	–3.7	456.9	100	59.6
6	206	44.9	23.2	5.0	221.7	48.4	5.9	1.3	1.5	0.4	458.3	100	46.4

Analysis of the thermal balance articles proves an increase in heat exchange effectiveness at organization of removal of combustion products under heated products [11].

In both smoke removal circuits, the change of the degree of masonry development (a decrease in the height of working space) from 1,500 to 1,150 mm in the experiments (1 and 3), (2 and 4) leads to an increase in efficiency by 1.36–1.37 times.

At a subsequent decrease in H from 1,150 to 800 mm in experiments в (3 and 5), (4 and 6), efficiency increased by 1.1 times.

4. 3. Designing combustion space of energy-technological devices and introduction in production

Based on the conducted research, the design was developed and the tunnel furnace was put into operation. It was for chemical and thermal treatment of metallic and non-metallic materials and products during their heating by the assigned schedule from 300 to 2100 K, keeping and cooling up to 350 K and above (Fig. 4). The process of annealing granulated salts of manganese-zinc ferrites in gas medium was implemented in the specified furnace.

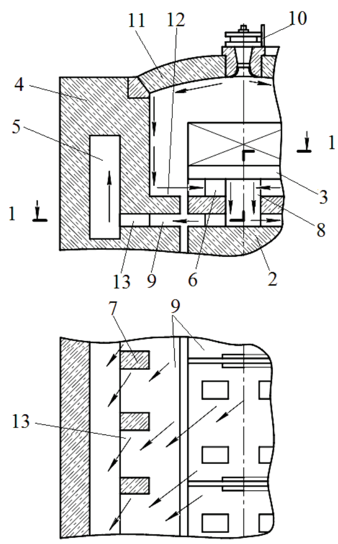

Fig. 4. Structural diagram of tunnel furnace: 1 — operating channel; 2 — car; 3 — working hearth of the car; 4 — side wall; 5 — longitudinal smoke channel; 6 — transverse smoke channels of the upper and lower levels; 7 — intermediate supports; 8 — a hole in the canalized hearth of the car; 9 — longitudinal smoke channel; 10 — flat flame burner; 11 — furnace arch; 12 — hearth of the furnace; 13 — smoke channel in the side wall

The principle of the combination of fuel input using flat flame burners, located above the heated product dispersed removal of combustion products under the heated product, is implemented in the furnace. In this case, a directed heat flow is formed under the heated product, which provides a multiple contact of phases (gas – solid body) at the top and at the bottom. This contributes to the intensification of heat and mass exchange inside the working space of the furnace.

The productivity of the furnace by the powder of the mixture of metal oxides is 500 t/year, the operating cycle is 24–26 h. The area of the furnace hearth is 26 m^2, the width of the operating space is 1.3 m. The furnace is equipped with 14 flat flame burners GPP-3 and GPP-4, minimum consumption of natural gas by the furnace is 120 m^3/h.

Compared with electric shaft and tunnel furnaces, Japanese gas rotating furnaces, the universal unit makes it possible to improve quality and ensure the 100 % output of suitable products by increasing the uniformity of temperature field on the heated material. At 1,500 K and above, the deviations are within ±5 K, at the temperature below 1,500 K, deviations are ±10 K). The thermal unit is characterized by compactness, low operating and capital costs, simplicity and ease of maintenance.

5. Discussion of results of studying the fire bench

Conducted experimental research into the influence of geometry and aerodynamics of the combustion chamber on the energy-technological indicators shows that a decrease in the height of a working space, equipped with flat flame burners, improves the fuel use. The effect occurs at the expense of heat exchange intensification, including direct convection and the resulting reduction in heat losses with flue gases and due to a decrease in the losses through the masonry. With a view to improving the technological energy efficiency of the combustion units equipped with flat flame burners and to reducing fuel consumption by 20÷30 %, it is possible to recommend setting the height of working space of 800÷1,000 mm (for structural reasons).

The distinctive feature of the furnace of the developed design is the elimination of discreteness and implementation of the stable continuous operation mode. The specified improvement was obtained due to the fact that longitudinal channels were made on the side surfaces of the cars and the furnace along the entire length of the latter. Thanks to this solution, the removal of combustion products from the furnace space through the canalized hearth of the cars into the longitudinal side channels, made in the walls of the furnace, goes on continuously. An additional aerodynamic compaction of the working space of the furnace is ensured at any speed of the cars' motion.

A significant advantage of the developed design of the combustion furnace is the possibility of using it for high-precision chemical and heat treatment of metallic and non-metallic materials. In addition, the energy technological effectiveness at arch heating of combustion units by flat flame burners and combustion products removal under the workpiece (lower smoke evacuation) is on average 1.3 times higher than at using the product removal circuit above the workpiece (lateral smoke removal), which is used in existing furnaces.

The scope of application of the tunnel furnace of the developed design is limited to the use for chemical and technological treatment of metallic and non-metallic materials and products during their heating by the assigned schedule from 300 to 2,100 K. The obtained recommendations were developed based on the studies carried out on the existing firing bench.

The prospect of subsequent studies is related to the search of the possibilities of enhancing efficiency of the thermal furnaces due to the changes in design characteristics of the combustion chamber. The second relevant direction of the research can be the problem of minimization of energy consumption in the process of chemical-thermal treatment of various workpieces.

6. Conclusions

1. Using a large-scale fire bench, the influence of the degree of masonry development (geometry) and aerodynamics of combustion chambers (circuits of removal of combustion products) on energy-technological indicators of the processes in the system gas-solid body was studied. It was found that a decrease in the height of the working space in the combustion chamber with flat flame burners improves fuel usage due to the heat exchange intensification, including direct convection. Energy-technological efficiency at the arch heating of the combustion furnace by flat flame burners and combustion products removal under the workpiece (lower smoke removal) is on average by 1.3 times higher than at the removal of products above the workpiece (lateral smoke removal).

2. It was found that a decrease in the height of the working space of the combustion chamber up to 800÷1,000 mm leads to saving fuel consumption by 20÷30 %.

3. The circuit of organization of aerodynamics of the heating space and, based on it, the design of the tunnel furnace for chemical and thermal treatment of metallic and non-metallic materials and products at heating from 300 to 2,000 K by the assigned schedule were developed. The design of the chamber enables continuous removal of combustion products from the furnace space through the canalized hearth of the cars into the longitudinal side channels in the walls of the furnace. The proposed aerodynamics of the combustion space ensures not only energy-technological advantages, but also the additional aerodynamic compaction of the working space of the furnace.

4. The rational mutual arrangement of flat flame burners and the smoke removal systems with the optimal height of the workspace can ensure high efficiency of the temperature field due to the multiple circulations of combustion products throughout the entire volume of the furnace. It determines the modern concept of designing thermal units for chemical and thermal treatment with heating by flat flame burners.

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