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IMPROVEMENT OF ENERGY EFFICIENCY IN THE OPERATION OF A THERMAL REACTOR WITH SUBMERGED COMBUSTION APPARATUS THROUGH THE CYCLIC INPUT OF ENERGY

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Досліджено утворення коливань контактуючих фаз (газ – рідина) в теплових реакторах, обладнаних апаратами зануреного горіння, за допомогою циклічного вводу енергії для інтенсифікації тепломасообмінних процесів і підвищення енергоефективності їх роботи. Аналітично і експериментально визначено характеристики процесу і їх вплив на інтенсивність турбулентних пульсацій. Запропонована і досліджена конструкція теплового реактора, обладнаного апаратом зануреного горіння з циклічним введенням зовнішньої енергії

Ключові слова: апарат зануреного горіння, циклічне введення енергії, гвинтовий перемішувальний пристрій, енергоефективність

Исследовано создание колебаний контактирующих фаз (газ – жидкость) в тепловых реакторах, оборудованных аппаратами погружного горения, с помощью циклического ввода энергии для интенсификации тепломассообменных процессов и повышения энергоэффективности их работы. Аналитически и экспериментально определены характеристики процесса и их влияние на интенсивность турбулентных пульсаций. Предложена и исследована конструкция теплового реактора, оборудованная аппаратом погружного горения с циклическим вводом внешней энергии

Ключевые слова: аппарат погружного горения, циклический ввод энергии, винтовое перемешивающее устройство, энергоэффективность

1. Introduction

Under contemporary conditions, 10–70 % of the cost of world product is the expenditures for energy resources. In connection with a total increase in the cost of energy resources in the world, much attention should be paid to the introduction of energy-efficient equipment, as well as technologies for the generation and consumption of energy, including thermal.

Given this, of special relevance are the scientific and technical developments, directed toward the creation of modern energy-efficient ecologically clean technologies. Relevant methods include the generation and consumption of thermal energy based on the synergy of hardware-technological design of the process.

The submerged combustion apparatuses (SCA) gained good reputation as a specific type of the heat-generating devices that operate based on the principle of combusting the gaseous or atomized liquid fuel directly in the heated medium. The thermal efficiency (performance efficiency, PE) of such apparatuses can be led almost to 100 % relative to the lowest heat of fuel combustion at the appropriate hardware-technological design and deep degree of the utilization of heat of waste gases.

Possibilities of the intensification of heat-mass transfer in SCA as the means of improving their operational energy efficiency are far from exhausted. Therefore we find it relevant to develop and study the thermal reactor, equipped with SCA with the cyclic introduction of external energy, to determine its performance characteristics and their impact on the energy effectiveness of reactor as a whole.

2. Literature review and problem statement

Studies of many authors in recent years have addressed different methods for the intensification of heat-mass transfer in different technologies in thermal reactors, equipped with SCA, for the purpose of improving the energy effectiveness of their work [1–3]. Designs of the evaporators for submerged combustion that operate on the liquefied natural gas are being improved [4]. One of the new directions towards increasing the effectiveness of the technology of submerged combustion is the application of apparatuses that work at elevated pressure, which makes it possible to increase the preheating temperature above the dew point [5]. An increase in the total pressure on the surface of the heated fluid leads to the higher boiling point of a liquid and allows a more efficient use of the energy of fuel and the heat of combustion products. However, this method is not economical, since additional energy is spent to increase the pressure, which reduces effectiveness of the heating process as a whole.

There are the more economical methods for increasing the energy effectiveness in the SCA operation. These include the imposition of outside oscillations on the contacting phases [6–8], pulsation of turbulent jets of the combustion products that enter the volume of fluid. This contributes to the instability of bubbling and dissipation of the energy of a jet.

A considerable number of articles deal with experimental and theoretical studies of characteristics of the turbulent jets, fed into the volume of fluid [9–11]. In this case, the methods of computer simulation and experimental measurements were employed to examine effect of the geometric parameters of a nozzle on the instability of a jet stream, the bubbling and dissipation of the jet energy [12, 13].

Paper [14] explored influence of design factors on the burner operation with the twisting of streams on the work of an apparatus as a whole.

In the gas-liquid systems, a rapid damping of the imposed oscillations occurs already at the first stage of the contact between phases. This process is more intensive in comparison with the single-phase systems because of the friction between phase flows. Given this, one should recognize that there is no promise to solve the problems on the intensification of heat-mass transfer by creating the pulsations of gas phase at the input to the apparatus. It is much more promising to use for the intensification the frequency-modulation oscillations, which are practically not damped in the disperse systems. The creation of pulsations at each step of the contact is not rational either, since it unavoidably leads to a significant complication of the mass-exchange apparatus and increases energy costs. Taking this into account, the outside oscillations are expedient to impose not on the entire layer (this yields little effect and energetically inappropriate). It is expedient instead in to concentrate the oscillations in the places with the highest efficiency of the contact between phases – in the moment when gas enters the fluid, as well as in the moment of destruction or formation of the gas-liquid layer.

The gas-liquid apparatuses still have a capacity to employ, for the purposes of intensifying the mass exchange process, the low-frequency oscillations, created with the help of external sources of energy (pulsators) [15]. In the pulsation reactors, the agitator is rigidly fixed inside a gas-liquid reactor. Pulses arrive at it from an autonomous oscillator – a pulsator. As a working medium in the creation of oscillations they use gas or liquid phases while the valve distributing mechanisms are widely applied as pulsators, as well as hydraulic devices with an electromagnetic actuator. The most frequently used is the pulsation reactor, which is a tank, inside which there is a full shaft with a disc, which makes reciprocating movement from an electromagnetic actuator [16].

One of the most promising trends is the intensification of mass exchange in the capacitive gas-liquid reactors, equipped with the submerged combustion apparatuses, built-in agitators (pulsators).

3. The aim and tasks of the study

The aim of present study is to improve energy efficiency of the work of thermal reactor with the submerged combustion apparatuses through the intensification of heat-mass transfer with the help of pulsator.

To achieve the set aim, the following tasks had to be solved:

– to examine the intensity of turbulent pulsations and their influence on the effectiveness of mass transfer as a whole, to determine performance characteristics of device with the cyclic input of external energy;

– to design a device for the cyclic input of external energy based on the step principle;

– to fabricate a device for the cyclic input of external energy, to assemble it under conditions of laboratory reactor with the system “gas – fluid”;

– based on the obtained research results, to develop a thermal reactor with the submerged combustion apparatuses and the cyclic input of external energy and to conduct its energy-technological tests.

4. Materials and methods for examining a thermal reactor with the cyclic input of external energy

Article [16] examines a thermal reactor (contact-modular thermal system) with the built-in submerged combustion apparatuses. An increase in its operational energy effectiveness is possible through the intensification of heat-mass transfer, agitating the interphase boundary gas – fluid by the cyclic input of energy into the interphase zone.

A cyclic input of energy is accomplished by changing the step ratio of a screw agitating device (SAD), which revolves at constant angular velocity ω (Fig. 1). The device is placed on the lateral side of reactor. Fig. 2 shows a chart of change in the introduced power by the screw agitating device.

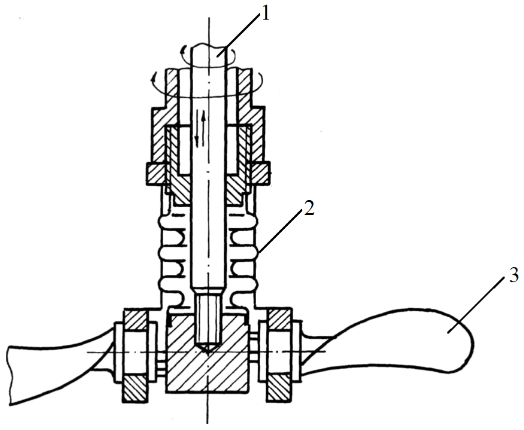


Fig. 1. Screw agitating device with a variable step ratio: 1 – shaft; 2 – screw device; 3 – blades of the external agitating device

The effect of increasing the speed of mass transfer at the cyclic input of external energy is achieved due to the additional turbulization of contacting phases gas – fluid. Heat dissipation in this case is described by a criterial equation of the following form [17]:

$$\frac{\alpha \cdot D}{\lambda} = c \cdot Re^{A} \cdot Pr^{B},$$

where α is the heat transfer coefficient of blades; D is the diameter of the agitating device; λ is the coefficient of thermal conductivity of the agitated medium; Re, Pr are the Reynolds and Prandtl criteria, respectively, for the process of agitation.

Constant c and powers of A and B depend on the conditions of the process, the type of agitating device, its dimensions and are determined experimentally. Consequently, heat emission in the thermal reactor grows proportionally to the increase in Re.

The Reynolds criterion for the agitating process is determined from relationship

$$\mathrm{Re}=\frac{n_e d^2 \rho}{\eta},$$

where n_e=k×n is the effective number of revolutions of the agitating device; k is the experimental coefficient; d is the diameter; ρ is the medium density; η is the dynamic coefficient of viscosity.

Thus, at other conditions being equal, with the rise in the effective number of revolutions of the agitating device, the large-scale turbulent eddies are generated, created by the stepped variation in the introduced power. In this case, the energy effectiveness of a thermal reactor as a whole improves. A change in the relative pulse duration (frequency and directions of oscillations) was accomplished with the help of methods, which provide cyclic regimes of interaction between fluid and gas using the microprocessor [17]. The microprocessor was assigned with the appropriate period, a pulse from the microprocessor arrived at a diaphragm valve. The diaphragm valve shifted the screw device at a specified step. In this case, the power of the screw agitating device changed and, as a result, the mass transfer. The research conducted on the laboratory reactor with a capacity of 50 l established that the cyclic input of external energy increases the process energy effectiveness in the liquid phase in 2–2.5 times. In this case, the optimal amplitude-frequency characteristics of the process are ensured.

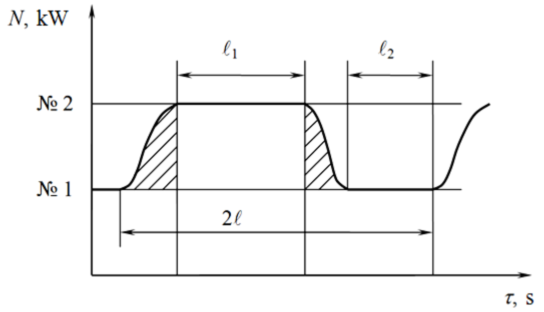


Fig. 2. Chart of change in the input power

Fig. 2 shows that the energy, transferred by pulsations (Fig. 2, selected area), grows with an increase in the introduced power.

5. Results of examining the intensity of turbulent pulsations

The estimation of an increase in the intensity of turbulent pulsations at cyclic input of external energy was conducted guided by the following considerations. In the apparatuses with SAD, the dependence of the introduced power N on the step ratio t takes the form [18]:

$$\left(N_1/N_2\right)=\left(t_2/t_1\right)^{1,7}, \tag{1}$$

where N_1, N_2, t_1, t_2 are the introduced power and step relations, respectively.

Thus, at cyclic variation in the step relation t, the power changes that is spent for the agitation and the interphase turbulent transfer of substance. In this case, at the same cyclic recurrence, the hydrodynamic situation in the apparatus changes (hydrodynamic head P, developed by SAD, medium consumption Q and other indicators).

Energy E, introduced into the reactor by the periodic law with period 2ℓ, is determined by the integral of Fourier series:

$$E=\int_0^{2\ell}\sum_{n=1}^{\infty}C_n \exp\left(\frac{n\pi i}{\ell}\right)\tau d\tau, \tag{2}$$

where C_n is the speed of device rotation at number of revolutions n, i is the step relation; n is the number of revolutions.

Then, the energy, transferred by pulsations (Fig. 2, selected region), is determined as:

$$\Lambda E\ \ \Delta E=\int_0^{2\ell}\sum_{n=1}^{\infty}C_n \exp\left(\frac{n\pi i}{\ell}\tau\right)d\tau-2N_1\ell-\left(N_2-N_1\right)\ell_1. \tag{3}$$

With a stepped variation in the step relation, hydrodynamic head P and consumption Q changes:

$$\Delta P=\Delta K_p n^2 d^2, \tag{4}$$

$$\Delta Q=\Delta K_Q n d^3, \tag{5}$$

where K_P, K_Q are the coefficients of head and consumption at different step relations, respectively.

The power, transferred by the pulsations in this case, is determined from expression:

$$\Delta N=\rho\Delta P\cdot\Delta Q=\rho\Delta K_p \Delta K_Q n^3 d^5. \tag{6}$$

By using a linear dependence of the coefficients of head on the coefficients of consumption that exists in region $0 \le K_P \le 1,4$ and $0,6 \le K_Q \le 1$ (Fig. 3):

$$\Delta K_p=a\Delta K_Q, \tag{7}$$

we find from equation (6) the value of ΔK_p at a cyclic variation in the introduced power:

$$\Delta K_p=\left(\frac{\Delta N a}{\rho n^3 d^5}\right)^{0,5}. \tag{8}$$

A change in the averaged speed of turbulent motion $\bar{U}$ is determined by formula:

$$\Delta\bar{U}^2=2\Delta P g=2K_p n^2 d^2 g. \tag{9}$$

Taking into account the equation of energy (3), a change in pulse speed U' is determined from dependence:

$$\Delta U'=\left\{\frac{-4ang^2}{\rho d}\left[\int_0^{2\ell}C_n \exp\left(\frac{n\pi i}{\ell}\tau\right)d\tau-2N_1\ell-\left(N_2-N_1\right)\ell_1\right]\right\}^{0,25}. \tag{10}$$

Resulting expression (10) makes it possible to estimate an increase in the intensity of turbulent pulsations in the apparatuses with cyclic input of energy:

$$\Delta I = \frac{\Delta U'}{\overline{U}},$$

where $\overline{U}$ is the averaged speed of turbulent flow over the period $t \geq 2\ell$.

Fig. 3 shows how with an increase in step relations *i* the coefficients of head and consumption grow accordingly, and, as a result, the power transferred by pulsations.

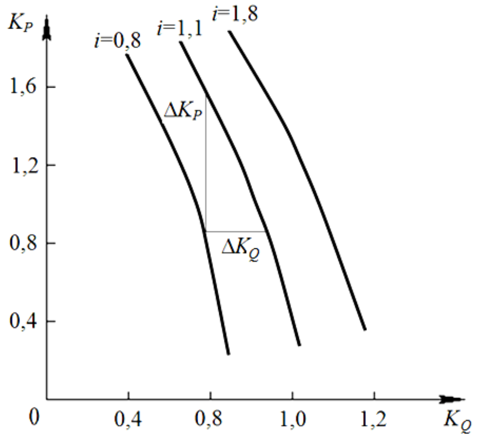


Fig. 3. Relation between coefficients of head K_P and consumption K_Q at different step relations i

6. Discussion of results of examining the obtained results

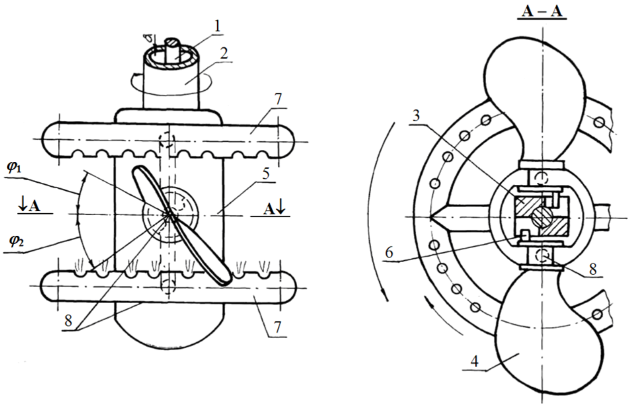
In the examined submerged combustion apparatuses the energy spectrum of eddies enhances the macro- and micro-agitation, as well as the mass transfer. In the SAD zone, there form both eddies with the large wave numbers that dissipate in the region of action of mechanical device and the large-scale turbulent pulsations with low wave numbers. For the large eddies, degeneration velocity of total kinetic energy of turbulence, expressed through the relative speed of its change, is substantially less than that for the eddies that correspond to large wave numbers. They pass significant distance in the device with SCA until, as a result of energy losses, they dissipate into small eddies. Eddies, which correspond to wave number K_d, have a characteristic linear dimension ℓ_k, commensurate to the sizes of gas pockets. By actively interacting with the latter, they turbulize the phase contact surface, which contributes to an increase in the rate of transfer. These processes proceed far from the zone of direct action of SAD, which contributes to the more uniform supply of external energy into the zone of action of SCA and its more effective use.

In the installations with built-in SCA and with the cyclic input of energy, the velocity of mass transfer can be additionally increased by creating the counter flows of gas and fluid (Fig. 4).

Shaft 1, hub 5, rigidly connected with it, with blades 4, fixed on it, and rod 2 make a rotational motion. Rod 2 with the help of a drive of translational motion makes a reciprocating movement with the programmed frequency and amplitude. Forward motion of rod 2 with the help of slider 3 and eccentric fingers 6, kinematically connected to it, and blades 4 is converted into continuous rotational motion of blades around own axis. Thus, according to the preset program, the magnitude and direction of speed of the axial flows change, as well as specific power, introduced to the heating installation with SCA. Air is fed through the annular space between shaft 1 and rod 2 inside a hollow hub. Through the radial channels in the necks of blades and drilling in the hub it enters upper or lower collector 7, depending on the angle of blade rotation. In the position of blades, shown in Fig. 4, the air is fed to the lower collector and is dispersed towards the flow of liquid phase (feed water at the input to the system) created by the blades. Countercurrent interaction of the contacting phases is realized at the turning of blades to angle $\varphi_1+\varphi_2$ and a change in the direction of axial flow. The air, preheated in the heating installation, which operates with SCA according to the principle of a "vapor pump" [14], enters the upper collector.

In addition to the high productivity and effectiveness of using the external energy, installations with built-in SCA and with the cyclic input of energy make it possible to conduct the controlled processes. They are easily reconfigured depending on the requirements to a technological regime.

In order to perform energy-technological tests of the designed device, the experimental installation with built-in SCA was equipped with a screw agitating device (SAD) (Fig. 5).



a *b*

Fig. 4. Agitator of the reactor with the cyclic input of energy and counter motion of gas phase: *a* — general view of device; *b* — cross-section along axis A—A; 1 — hollow shaft; 2 — rod; 3 — slider; 4 — blades of the screw agitating device; 5 — detachable hub; 6 — eccentric fingers; 7 — gas collectors; 8 — gas-distributing openings

The installation operates in the following way: cooled water from the heating system through a branch pipe (6) enters tank (1) with installed SCA (2) and SAD (3). The shaft of SAD with the blades mounted on it is placed on the mark of the phase boundary, formed by the work of SCA (Fig. 5). Partitions (5) separate SCA and SAD. When entering the zone of SAD action, which operates according to the set program, the fluid is turbulized. Large-scale turbulent pulsations, moving in the direction of the action zone of working SCA, dissipate into small eddies, which contributes to the intensification of the heat-mass transfer process as a whole.

Flue gases (II), cooled to 100–120 °C, enter heat exchanger (5), then heat the air that enters the air collector of SAD to 50–60 °C, which is dispersed towards the flow of liquid phase created by the blades. Table 1 gives selected indicators of the testing.

Table 1

Results of the thermo-technical testing of the screw agitating device built into the system

Parameter title	Dimensionality	Designation	Parameter value
Load	%	–	96.4
Thermal capacity	kW	Q_c	615.0
Water consumption	m^3/s	G	0.0046
Gas consumption by the counter	m^3/s	V_c	0.0159
Gas consumption under normal conditions	nm^3/s	V_c	0.0172
Water temperature at the inlet to heater	°C	$T_{w.in}$	40.5
Temperature of gas that is supplied to combustion	°C	$T_{g.in}$	20
Temperature of flue gases	°C	$T_{f.out}$	120
Temperature of air supplied to SAD	°C	T_{air}	50
Water temperature at the outlet of heater	°C	$T_{w.out}$	78
Inlet gas pressure	MPa	$P_{g.in}$	0.0000108
Gas pressure before the counter	kPa	$P_{g.c}$	17.00
Gas pressure before the burner	kPa	$P_{g.b}$	12.500
Air pressure before the burner	kPa	$P_{a.b}$	7.5
Underpressure after the burner	Pa	P_b	347.00
Content in dry products: oxygen	%	O_2	4.3
Carbon dioxide	%	CO_2	9.4
Content in dry combustion products brought to α=1 (under normal conditions): carbon oxide	mg/m^3	CO_2	48.2
Nitrogen oxides	mg/m^3	NO_2	56.8
Excess air ratio	–	α	1.23
PE by direct balance Efficiency by direct balance	%	η_d	98.6

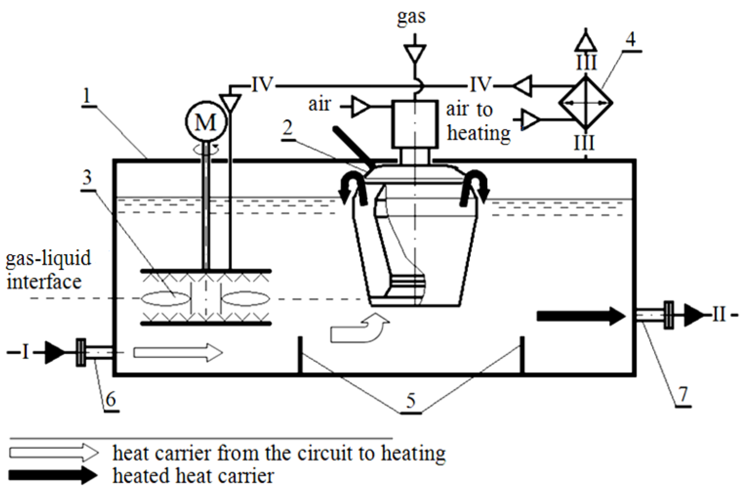


Fig. 5. Schematic of the screw agitating device, built into a thermal reactor equipped with submerged combustion apparatus: 1 — tank filled with a heat carrier; 2 — submerged combustion apparatus; 3 — screw agitating device; 4 — heat exchanger; 5 — partition; 6 — feed of fluid to the system; 7 — output of the heated heat carrier to the consumer; material flows: I — heat carrier from the circuit; II — heated heat carrier; III — combustion products; IV — heated air

An analysis of results of the performed thermo-technical tests of a thermal reactor with SCA and the cyclic input of energy with the help of a screw agitating device reveals that energy efficiency of the thermal system corresponds to high energy-technological requirements. Performance efficiency of the thermal reactor by direct balance equals 98.6 %.

7. Conclusions

1. We examined influence of the turbulent pulsations on the effectiveness of mass transfer. It is established that the cyclic input of external energy increases mass transfer by 2–2.5 times, as well as energy efficiency of the process as a whole.

2. A design of the device for the cyclic introduction of pulses of external energy is proposed for the intensification of heat-mass transfer and improvement of energy effectiveness of the work of thermal reactors with the built-in submerged combustion apparatuses. A distinctive feature of the thermal reactor with the cyclic input of energy is in the fact that air, preheated in the

thermal installation with SCA, which operates according to the principle of a "vapor pump", enters the upper and lower collectors of SAD. In this case, air is dispersed depending on the angle of blade rotation, which contributes to the turbulization of phase boundary, which improves energy efficiency of reactor operation.

3. We fabricated, assembled and verified under conditions of a laboratory reactor with the system gas-fluid the device for the cyclic input of external energy.

4. Based on the conducted studies, we developed a thermal reactor with the built-in submerged combustion apparatuses and the cyclic input of external energy for creating the turbulent pulsations that operates on the principle of a "vapor pump". The energy-technological indices of the developed thermal reactor meet the world requirements: the content of nitrogen oxides does not exceed 56.8 mg/m^3 at high-temperature water heating – to 70–80 °C. Thermodynamic performance efficiency of the thermal reactor reaches 98.6 %.

References

1. Rao, D. N. Direct contact heat transfer – a better way to high efficiency and compactness [Text] / D. N. Rao, M. F. Mohtadi, M. A. Hastaoglu // The Canadian Journal of Chemical Engineering. – 1984. – Vol. 62, Issue 3. – P. 319–325. doi: 10.1002/cjce.5450620305
2. Gong, X. Emissions and thermal efficiency investigation of a pressurized submerged combustion evaporator [Text] / X. Gong, Z. Liu, H. Jiang // International Journal of Low-Carbon Technologies. – 2012. – Vol. 7, Issue 4. – P. 257–263. doi: 10.1093/ijlct/cts059
3. Ribeiro, C. P. Gas-Liquid Direct-Contact Evaporation: A Review [Text] / C. P. Ribeiro, P. L. C. Lage // Chemical Engineering & Technology. – 2005. – Vol. 28, Issue 10. – P. 1081–1107. doi: 10.1002/ceat.200500169
4. Han, C.-L. Experimental investigation on fluid flow and heat transfer characteristics of a submerged combustion vaporizer [Text] / C.-L. Han, J.-J. Ren, Y.-Q. Wang, W.-P. Dong, M.-S. Bi // Applied Thermal Engineering. – 2017. – Vol. 113. – P. 529–536. doi: 10.1016/j.applthermaleng.2016.11.075
5. Gong, X. L. Model Analysis of Pressure Fluctuation in the Pressurized Submerged Combustion [Text] / X. L. Gong, Q. Feng, Z. L. Liu, W. J. Tang // Advanced Materials Research. – 2013. – Vol. 779-780. – P. 425–428. doi: 10.4028/www.scientific.net/amr.779-780.425
6. Tovazhniansky, L. L. Teploenergetika pogruzhnogo gorenia v reshenii problem teplosnabzheniya i ekologii Ukraine [Text] / L. L. Tovazhniansky, L. P. Pertsev, V. P. Shaporev et. al. // Integrirovannie Technologii i Enenrgosnabzenie. – 2004. – Issue 3. – P. 3–12.
7. Niegodajew, P. Experimental study of gas-liquid heat transfer in a 2-phase flow in a packed bed [Text] / P. Niegodajew, D. Asendrych // Journal of Physics: Conference Series. – 2016. – Vol. 745. – P. 032139. doi: 10.1088/1742-6596/745/3/032139
8. Benbelkacem, H. Modeling of a gas-liquid reactor in batch conditions. Study of the intermediate regime when part of the reaction occurs within the film and part within the bulk [Text] / H. Benbelkacem, H. Debellefontaine // Chemical Engineering and Processing: Process Intensification. – 2003. – Vol. 42, Issue 10. – P. 723–732. doi: 10.1016/s0255-2701(02)00074-0
9. Bie, H.-Y. Effect of Nozzle Geometry on Characteristics of Submerged Gas Jet and Bubble Noise [Text] / H.-Y. Bie, J.-J. Ye, Z.-R. Hao // Journal of Laboratory Automation. – 2016. – Vol. 21, Issue 5. – P. 652–659. doi: 10.1177/2211068215584902
10. Lu, R. Theoretical and experimental study on underwater jet characteristics from a submerged combustion system [Text] / R. Lu, X. H. Qin, D. Z. Wu, H. W. Wang // IOP Conference Series: Materials Science and Engineering. – 2013. – Vol. 52, Issue 7. – P. 072017. doi: 10.1088/1757-899x/52/7/072017
11. Arghode, V. K. Jet characteristics from a submerged combustion system [Text] / V. K. Arghode, A. K. Gupta // Applied Energy. – 2012. – Vol. 89, Issue 1. – P. 246–253. doi: 10.1016/j.apenergy.2011.07.022
12. Dahikar, S. K. Experimental and computational fluid dynamic study of reacting gas jet in liquid: Flow pattern and heat transfer [Text] / S. K. Dahikar, J. B. Joshi, M. S. Shah, A. S. Kalsi, C. S. RamaPrasad, D. S. Shukla // Chemical Engineering Science. – 2010. – Vol. 65, Issue 2. – P. 827–849. doi: 10.1016/j.ces.2009.09.035
13. Miao, T. C. Numerical study on the effect of a lobed nozzle on the flow characteristics of submerged exhaust [Text] / T. C. Miao, T. Du, D. Z. Wu, L. Q. Wang // IOP Conference Series: Materials Science and Engineering. – 2016. – Vol. 129. – P. 012066. doi: 10.1088/1757-899x/129/1/012066
14. Yoon, H. K. Development of a High Load Submerged Combustion Burner [Text] / H. K. Yoon, K. S. Song, S. N. Lee // International Journal of Fluid Mechanics Research. – 1998. – Vol. 25, Issue 1-3. – P. 276–284. doi: 10.1615/interjfluidmechres.v25.i1-3.240
15. Nikolsky, V. E. Intensification of heat-mass exchange processes in the immersed burning apparatus by contacting phases oscillation [Text] / V. E. Nikolsky // ScienceRise. – 2015. – Vol. 7, Issue 2 (12). – P. 38–42. doi: 10.15587/2313-8416.2015.46987
16. Nikolsky, V. E. Development and study of contact-modular heating system using immersion combustion units [Text] / V. E. Nikolsky // Eastern-European Journal of Enterprise Technologies. – 2015. – Vol. 4, Issue 8 (76). – P. 31–35. doi: 10.15587/1729-4061.2015.47459
17. Zadorsky, V. M. Teoriya tekhnicheskih sistem [Text]: ucheb. pos. / V. M. Zadorsky. – Dnepropetrovsk, 2016. – 442 p.
18. Strenk, F. Peremeshivaniye i apparati s meshalkami [Text] / F. Strenk. – Leninrad: Khimiya, 1975. – 268 p.