UDC 697.244+621.3.082.1
DOI: 10.15587/1729-4061.2017.103868

APPLICATION OF ELECTROMAGNETIC FIELDS FOR INTENSIFICATION OF HEAT AND MASS EXCHANGE IN COMBINED GAS-LIQUID PROCESSES

Аналітично і експериментально досліджено вплив магнітних і електричних полів з градієнтом напруги в напрямку руху контактуючих фаз газ-рідина. Виконано вибір найбільш ефективного методу впливу на процес тепломасообміну з метою підвищення енергоефективності апаратів погружного горіння. Запропоновано метод контролю коливань у контактуючих фазах газ-рідина з використанням вібраційного вимірювального перетворювача з циліндричним резонатором

Ключові слова: інтенсифікація тепломасообмінних процесів, магнітне і електричне поле, циліндричний резонатор, індукційний приймач

Аналитически и экспериментально исследовано влияние магнитных и электрических полей с градиентом напряжения в направлении движения контактирующих фаз газ-жидкость. Выполнен выбор наиболее эффективного метода воздействия на процесс тепломассообмена с целью повышения энергоэффективности аппаратов погружного горения. Предложен метод контроля колебаний в контактирующих фазах газ-жидкость с использованием измерительного преобразователя с цилиндрическим резонатором

Ключевые слова: интенсификация тепломассообменных процессов, магнитное и электрическое поле, цилиндрический резонатор, индукционный приемник

V. Nikolsky
Doctor of Technical Sciences, Professor*
O. Oliynyk
PhD, Associate Professor
Department of Computer-integrated Technologies and Metrology**
E-mail: oleinik_o@ukr.net
V. Yaris
PhD, Associate Professor
Department of chemical enterprises equipment**
E-mail: equipment_chem@udhtu.edu.ua
I. Reshentniak
PhD, Associate Professor*
*Department of Energetic**
**Ukrainian State University of Chemical Technology
Gagarina ave., 8, Dnipro, Ukraine, 49005

1. Introduction

Intensification of heat and mass transfer in combined gas-liquid processes and apparatuses provides an opportunity to increase productivity of devices with a reduction in their dimensions, metal consumption, cost, operating costs. Intensification makes it possible to obtain new effects commensurate and sometimes even surpassing by importance the main target effects (reduction of inlay on the internal surfaces of devices, higher selectivity of chemical processes, lower energy costs) [1].

At present, various methods for intensifying heat and mass transfer have been proposed and investigated. For this purpose, flow turbulators are used widely on the surface, flow swirling with swirlers installed at the entrance to the apparatus, mixing gas bubbles with the gas flow, rotating or vibrating the heat and mass exchange surface and influencing the flow with electrostatic, magnetic fields [2]. In this case, effectiveness of intensification for various methods at substantially differing energy costs is different and is evaluated in each instance.

Submersible combustion devices (SCD) form a special class of gas-liquid thermal devices of bubbling type. The method based on a contact heating of water (final or intermediate heat transfer medium) in SCD is the most universal and energy efficient. The devices and installations operating on their basis are characterized by efficiency greater than 100 % with respect to the lowest heat of combustion [3].

Abilities of intensification of heat and mass transfer in SCD as a means of energy efficiency of their operation are far from being exhausted [4].

Therefore, development of a gas-liquid thermal reactor equipped with an SCD, which generates oscillation of contacting phases by imposition of electromagnetic fields should be considered an urgent issue.

2. Literature review and problem statement

A significant number of traditional and up-to-date methods of intensifying technological processes taking place in gas-liquid systems are known [1]. It is known that magnetic and electric fields affect heat and mass transfer processes in various systems [5]. In a number of works experimental data confirming influence of electromagnetic fields on intensification of metal dissolution processes, clarification of industrial solutions and wastewater [6], mixing [7], bubbling [8] and reaction processes [9] are presented. However, the causes of influence of magnetic and electric fields on the mass-exchange and chemical processes and effects that arise upon exposure have not yet been studied sufficiently. This issue significantly hampers a widespread practical use of these methods of intensifying heat transfer process and increasing energy efficiency of gas-liquid processes. Therefore, studies of the effect of electromagnetic fields and other methods of intensifying heat and mass transfer in gas-liquid processes should be recognized as relevant. Choice of an optimal method of action on the processes of heat and mass transfer occurring in thermal gas-liquid devices is a key problem in solving the issues of improving energy efficiency of equipment.

At the same time, despite the urgency of the problem of intensification of heat and mass transfer in thermal gas-liquid devices, the issue of controlling electro-hydraulic effects was practically not considered in the literature. These effects occur in contacting gas-liquid phases when electric and magnetic fields are applied to them. The maximum influence of the imposed fields and natural vibrations of the medium arises when resonance effect is achieved [10]. However, to date, there are no data on methods for measuring resonant frequencies in thermal reactors with SCD. There are no sufficiently universal procedures and equipment at present although a large number of methods are known that are successfully used in special cases.

In [11], a description of pendant microchannel resonators is presented, a theoretical model of suspended microchannel resonators is described taking into account electrostatic field and internal liquid. The study results show that the system is subject to instability when velocity of the stationary flow approaches a critical velocity.

Vibrofrequency measuring transducers in which resonant measuring sensor is mechanically connected with the studied oscillating medium [12] are the most widely used devices. The main disadvantage of such measuring instruments is presence of nonlinearity that complicates choice of the resonator type [13]. A self-oscillating system of vibrofrequency sensors with a varying character of nonlinearity proposed in [14] substantially simplifies development of resonator sensors.

Thus, study of effect of electric, magnetic fields and other methods of influence on the process of mass transfer in the gas-liquid layer for the purpose of intensification is an actual scientific task. Choice of a method for controlling emerging electrohydraulic effects in the phase contact zone is a promising aspect of solving the problem of controlling heat and mass exchange processes in thermal reactors with an immersion combustion device.

3. The study objective and tasks

This paper objective was evaluation of the effect of electric and magnetic fields imposed on the gas-liquid interface on the process of intensification of heat and mass exchange and choice of the most effective method for influencing the gas-liquid interface and the method for controlling emerging electrohydraulic effects for improving energy efficiency.

To achieve this objective, it was necessary to solve the following tasks:

– investigate influence of electric and magnetic fields having a gradient of tension in the direction of motion of the contacting phases on the process of mass transfer between phases;

– determine kinematic and power characteristics in the wave field generated by interaction of phases when magnetic and electric fields are superimposed on the interface between them;

– develop a method and device for imposing an optimal effect on the interface between the phases of the gas-liquid system to amplify oscillations of the contacting phases in order to intensify heat and mass transfer in reactors equipped with submersible combustion devices;

– develop a method for controlling forced oscillations of contacting phases for controlling thermal reactors with a submersible combustion device.

4. Study of the influence of magnetic and electric fields on the energy efficiency of thermal gas-liquid systems

The use of magnetic and electric fields with deliberately created intensity gradients to enhance effect of heat and mass transfer in production processes is based on the corollaries of thermodynamics of irreversible processes.

Studies of the effect of magnetic fields on the mass exchange were carried out on a film-type device to obtain a stable phase contact surface. This condition enables elimination of distortion of the results due to the structure of the gas-liquid layer.

The studies provided following operation options for the device: absorption of carbon dioxide or oxygen by water; desorption of carbon dioxide, oxygen and ammonia with nitrogen; circulation of the liquid phase in order to determine equilibrium concentration. Elements of stabilization and control of gas and liquid phase flows were provided in the experimental setup.

The film device (Fig. 1) was made of a non-magnetic material (stainless steel) and equipped with a rod of soft magnetic steel of a stepped conical shape. Such a design provides magnetic fields of non-uniform intensity in the gaps of six pairs of electromagnet poles. Electromagnets were located outside the device on U-shaped sandwiches of transformer steel. The electric circuit for electromagnet power supply from a constant (pulsating) current source made it possible to implement various variants of their switching.

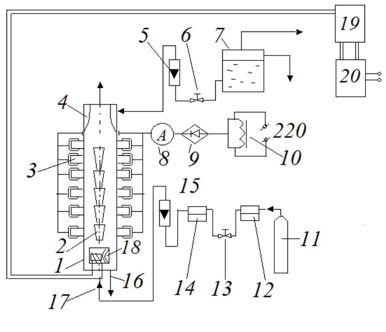

Fig. 1. Experimental setup diagram: pipe (1); rod (2); electromagnet (3); water distributor (4); rotameter (5); valve (6); vessel (7); milliammeter (8); rectifier (9); autotransformer (10); cylinder with CO_2 (11); reducer (12); valve (13); flow regulator (14); rotameter (15); pipes (16, 17); vibrofrequency sensor (18); oscillograph (19); power supply unit (20)

The study of local efficiency of phase contact was carried out by determining mass transfer coefficient the value of which was calculated taking into account the comparative analysis of the liquid mass in the sampler at various electric field voltages in accordance with the procedure as in [15]. Sampling of only liquid phase was carried out in the pipe (1) from two-phase flows using a sampler made of a porous material. Efficiency of the mass transfer process was estimated based on plotted experimental curves (Fig. 2).

Characteristic displacement of extreme values of mass transfer coefficients into the region of low currents (magnetic field intensities) was observed for the case of absorption of carbon dioxide with distilled water (curves 4, 5). This made it possible to assume influence of the salt composition of water on the process of mass transfer for the case under consideration. However, the nature of dependence of mass transfer coefficients on the direction of magnetic fluxes indicates that the salt composition of water is not the only determining factor of this process.

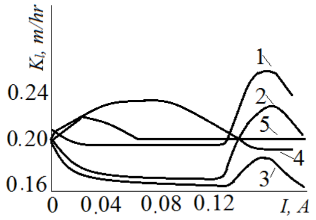

Fig. 2. Dependence of the mass transfer coefficients K_l in the liquid phase on current I in the electromagnets windings: alternating in direction magnetic fields (1); unidirectional fields (3); non-uniformly alternating fields (2, 4, 5)

For the case of oxygen absorption (curves 2, 3), there was no noticeable decrease in the mass transfer coefficients at low magnetic field intensities. However, even in this case, the extreme values were noted approximately at the same current values like in carbon dioxide absorption.

The variation of the mass transfer coefficient during superposition of magnetic fields is apparently associated with the magnetic polarization of gas and liquid molecules and intensification of their motion, especially in the case of direction alternation and heterogeneous topography (presence of gradients) of magnetic fields. Besides, some influence was also exerted by pulsations of contacting phases caused by the superposition of pulsating magnetic fields generated by electromagnets fed by directionally constant current pulsating with a frequency of 100 s^{-1}.

Since the hydrodynamic situation of the process determines mass transfer between the phases, an attempt was made in the paper to qualitatively evaluate the effect of magnetic fields on the hydrodynamic situation when single gas bubbles and liquid are contacting.

A facility consisting of a glass chamber filled with process water and placed between the electromagnet poles was used for the studies. Study of obtained kinograms made it possible to note influence of magnetic field on the shape and velocity of gas bubbles. When the magnetic field was turned on, the gas bubbles with shape close to spherical acquired the form of ellipsoids of revolution with an axis ratio of about 0.8, velocity of bubble rise was reduced by ~20 %.

The results of study of the effect of magnetic fields on mass transfer in gas-liquid systems indicate that magnetic fields, even at low intensities, can be a means of intensifying mass-exchange processes in installations equipped with SCD.

Influence of electric fields on mass exchange was studied on a 0.03 m diameter, 1.15 m high film-type column. To generate electric field, the glass column was placed inside a winding of aluminum foil layer, grounded at the column axis and a nichrome wire serving as a corona electrode was passed inside. This circuit made it possible to connect a nichrome wire to the pole of a high-voltage source.

Efficiency of the mass transfer process under the action of electric field was estimated by a procedure used to study effect of magnetic field [15]. Dependence of the experimentally determined mass transfer coefficient on the intensity of electric field at various flow rates in the tube (1) is shown in Fig. 3.

The study results indicate that the electric field has a significant effect on absorption of carbon dioxide (Fig. 3). The increase in mass transfer intensity can be explained by the fact that water molecules are polarized and oriented along the absorber wall attracting ionized CO_2 molecules. Negative CO_2 ions had a higher speed of motion [16].

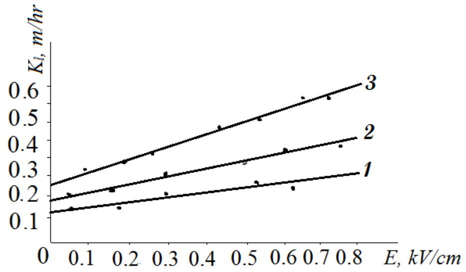

Fig. 3. Dependence of the mass transfer coefficients K_l on electric field intensity E at liquid flow rates: 0.019 m^3/h (1); 0.024 m^3/h (2); 0.031 m^3/h (3)

The investigations, which were carried out in [16] indicate that the use of electric and magnetic fields for intensification of synerergic processes in the diffusion region can be no less promising. In the implementation of this method, an electric current was induced and, consequently, electric fields in the liquid phase. This caused microturbulization of the liquid in electromagnetic fields and lead to an intensification of mass transfer. However, realization of the method is only possible in an electrically conductive medium. The industrial implementation of this method requires a cumbersome technological tool for inducing electromagnetic fields (especially for large-size SCDs). In addition, higher energy costs are required. This is due to the fact that a part of electrical energy is lost on heating windings of electromagnets and liquids, energy conversion, overcoming magnetic resistance of the device material and air gaps between the medium and magnets.

The disadvantages of imposing electric fields on the contacting phases are eliminated by their preliminary ionization [17]. Ionization of the contacting phases makes it possible to substantially intensify the process of mass transfer at low energy and material costs and in those cases when it is impossible to intensify the process with the help of electromagnetic fields. In addition, it is feasible to regulate rate of the mass transfer process (accelerating or slowing it down) by varying degree of ionization of the contacting phases: gas (vapor) and liquid phase in SCD. In this case, the degree of ionization depends on the change in the magnitude of electric potential at the ionizer electrodes (located in the SCD, near the phase interface).

For a comparative analysis of the last two methods of intensification, investigations were carried out with a film absorption column made of a nonmagnetic material. The column structure provides for creation of 5 belts of electromagnetic fields with an induction of 0.05 T at a countercurrent of contacting phases (water and carbon dioxide). The fields were induced by 15 electromagnets, 3 electromagnets in each belt connected to a three-phase alternating current line (Fig. 1). The total power consumption of the plant was 1300 W.

When the ionization method was realized, the installation (Fig. 1) was equipped with an ionizer installed in the line for gas supply to the column (Fig. 4).

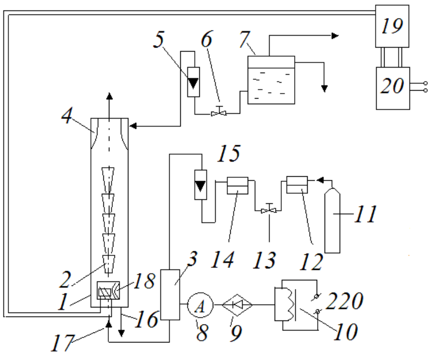

Fig. 4. Diagram of the experimental setup with an ionizer: pipe (1); rod (2); ionizer (3); water distributor (4); rotameter (5); valve (6); vessel (7); milliammeter (8); rectifier (9); autotransformer (10); cylinder with CO_2 (11); reducer (12); valve (13); flow regulator (14); rotameter (15); pipes (16, 17); vibrofrequency sensor (18); oscillograph (19); power supply unit (20)

The gas introduced into the column was preliminarily ionized in an electric field pulsating at a frequency of 3000 s^{-1}. The electric field was induced with the help of electrodes to which negative electric potentials variable by magnitude were applied. The load for the phases in both series was maintained at equal levels. Intensity of the process of ionization of the contacting phases (water and carbon dioxide) was estimated by the magnitude of the mass transfer coefficient. The mass transfer coefficient was determined in accordance with the procedure described previously. When the ionization method was realized, a 2.7 fold growth of the values of the mass transfer coefficient (in comparison with the values obtained under direct action of the magnetic field) was observed. The consumed power of the ionizer was 7 W. Thus, energy consumption in using the ionization method was 185 times lower than with the use of the installation with electromagnets.

It is known [18] that many chemical processes can be intensified utilizing energy of the shock wave. There are indications that when the energy of the shock wave is applied, the processes of cracking, oxidation, synthesis, pyrolysis, polymerization, nitrogen oxide production directly from air [19] can be realized.

One of the simplest methods of obtaining impact waves of controlled parameters is to use the electrohydraulic effect that occurs when an electric discharge in a liquid is applied. This effect is widely used for knocking out rods from castings in the finishing operations of foundry production, in building electrohydropulse presses and other units. Electropulse vibrators based on the electric discharge technology have also been developed. They are used, for example, to intensify the diffusion process of removing gas inclusions during casting steel into molds. Electrohydraulic mixers for high-viscosity liquids were developed and recommendations were given for choosing their main design parameters.

Mass exchange between a solid and a liquid in which an oscillatory process is excited by means of spark discharges of various frequencies was considered in [20]. Acceleration of the mass transfer process was raised by a factor of 2.3–5. It was shown that the mass transfer coefficient is a function of frequency of spark discharges. Maximum values of the mass transfer coefficient were achieved at a frequency about 200 s^{-1} (for discharges having energy of 0.5–1 J, duration 25 μs at water temperature of 18 °C). This work has made it possible to outline prospects of application of electrospark and mixing devices for intensification of heat and mass transfer processes in installations equipped with SCD.

There are also works devoted to intensification of heat transfer in high-frequency electric fields, study of external mass transfer in a solid-liquid system under the action of high-voltage spark discharges [21]. Work [22] describes development of a high-intensity electrocontactor for extraction separation of petroleum distillates by selective solvents. However, there is no information on the practice of using electric discharges in liquids for intensification of gas-liquid processes. Meanwhile, the electro-hydraulic shock is of considerable interest in terms of its use as a powerful factor of intensification of gas-liquid processes including in installations with SCD. With an electrical discharge in a liquid (discharge time 10–100 μs) in the discharge channel, the substance passes into the plasma state. In this case, a huge amount of energy is released, temperature rises to several thousand degrees.

On assumption that these electro-hydraulic impact effects are primary, presence of secondary effects cannot but noted. Secondary effects consist in origination of electric and magnetic fields with a rapidly varying in time intensity or appearance of a shock wave with a steep leading pulse edge (acceleration reaches 300 g, pressure near the discharge channel is 5×10^{10} Pa).

Each factor of the electropulse discharge in a liquid is per se a powerful means of intensification (electric and magnetic field, high temperature, impulsive pressure change, etc.). Thus, with the combined effect of all these factors, one can expect a mutual enhancement of the effect of intensification of heat and mass transfer processes. An important point is also that the modern power equipment of electrohydraulic units allows one to vary discharge frequency in the range of 0–40 s^{-1}. For many technological processes taking place in gas-liquid systems, including in SCD, the optimal frequency of vibropulse factors is in the range of 10–20 s^{-1}. Hence, it is necessary to recognize an extraordinary temptation to use this effect to intensify processes of heat and mass transfer in gas-liquid systems, including SCD.

To solve the problem of controlling heat and mass exchange processes in thermal reactors with an immersion combustion device, it is necessary to control the electrohydraulic effect that determines the speed of the interaction process of the contacting phases.

5. Control of the oscillation process in contacting phases

When gas and liquid are contacting in an experimental setup (Fig. 1, 2), medium vibrations arise a frequency characteristics of which are determined by a variety of factors: design of the installation chamber and the CO_2 distributor, velocities of the phases and their physicochemical properties, pressure, temperature. Thus, in the experimental setup, which serves to simulate operation of the submerged combustion devices, a complex oscillatory system is formed upon contact of the phases. The main task in development of a control system for heat and mass exchange processes in thermal reactors with a submersible combustion device is the choice of a control method that will ensure obtaining information reliably characterizing the course of the process.

To control the oscillations arising from the use of electric and magnetic fields and due to electric spark discharge, it was proposed to use a vibrofrequency measurement method.

Vibrofrequency sensors are advantageously distinguished by their ability of telecasting measurement information over very long distances with no use of special expensive devices and communication channels. They are convenient for precision measurements (0.1–0.5 % of the measured value, or 0.04–0.25 % of the upper limit of measurement) [23].

It was proposed to use a multifunctional vibrofrequency measuring transducer with a cylindrical-type resonator.

The transfer function of such a resonator has the form [14]:

$$W_{m.n}(p)=\frac{K_{m,n}}{T_{m,n}^2\cdot p^2+2\cdot\xi_{m,n}\cdot T_{m,n}\cdot p+1},\tag{1}$$

where $K_{m,n}$, $T_{m,n}$, $\xi_{m,n}$ are the static transmission coefficient, the time constant and the degree of calming the resonator oscillations on the mode shape m×n, where m is the number of half-waves along the generatrix, and n is the number of waves along the circumference.

$$K_{m,n}=\frac{C^q_{m,n}}{d_{m,n}},\tag{2}$$

$$T^2_{m,n}=\frac{1}{\omega^2_{m,n}}=\frac{\rho\cdot h}{d_{m,n}},\tag{3}$$

$$\xi_{m,n}=\frac{\delta}{2\cdot\sqrt{\rho\cdot h\cdot d_{m,n}}}=\frac{1}{2\cdot Q_{m,n}},\tag{4}$$

where $d_{m,n}$ is the effective rigidity of the resonator; $Q_{m,n}$ is quality factor of the resonator on the corresponding mode shape, ρ, h are material density and the resonator wall thickness; δ is coefficient of energy losses on this mode shape.

An induction receiver of oscillations was used as a converter of mechanical oscillations of cylindrical resonator into electrical signal (Fig. 5).

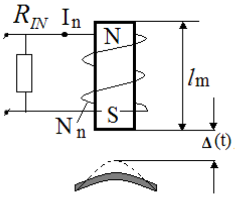

Fig. 5. Device of the oscillation receiver: l_m is length of the permanent magnet; N_n is number of the receiver coils; Δ is the nominal gap between the cylindrical resonator and the coil; R_{in} is input resistance of the amplifier, the source of the excitation signal

In a dynamic mode, connection between the Laplace transforms of the voltage at the output of the induction transducer $U_t(p)$ and the average displacement of the surface portion of the cylindrical resonator is determined by the transfer function:

$$W_n(p)=\frac{U_n(p)}{W_i^{cp}}=\frac{K_n\cdot p}{T_n\cdot p+1}.\tag{5}$$

Parameters of the receiver transfer function have the following form [14]:

$$K_t=\frac{H_0\cdot B_0\cdot S_M\cdot K_r\cdot R_{in}\cdot N_n}{(B_0+H_0+K_{ret})\cdot(R_{in}+R_k)},\tag{6}$$

$$T_n=\frac{L_c}{(R_{in}+K_c+R_c)},\tag{7}$$

where K_t is the static transmission coefficient; T_n is the time constant; R_{IN} is electric input resistance of the amplifier; N_n is the number of receiver coils working per one input of the differential amplifier; H_0, B_0 are intensity, magnetic field induction (parameters of the working point in the magnet demagnetization curve); K_R is coefficient of return by the demagnetization curve of the permanent magnet (K_R =0.2...0.3); S_M is the cross-sectional area of the permanent magnet; N_n is the number of turns of the coil in the induction receiver; K_c is the number of coils of the receiver working per one input of the differential amplifier.

Location of the receiver coils relative to the nodes and antinodes of oscillations of the cylindrical resonator is taken into account by coefficient K_{ni}. If the receiver coils are located in antinodes of the excited oscillations of the resonator, then the values of K_{ni}, are calculated by the formula

$$K_{ni}=\frac{4}{n\cdot m\cdot\pi\cdot x_0}\cdot\sin\frac{m\cdot\pi\cdot x_0}{2\cdot l}\cdot\sin\frac{n\cdot\theta_0}{2},\tag{8}$$

where x_0, θ_0 are linear and angular dimensions of the coil.

To evaluate accuracy of the chosen measurement method, a cylindrical resonator with design parameters was used: resonator length L=32 mm, median radius R=20 mm, wall thickness h=0.1 mm. The measured phase shifts on the inductances (15 mH) are Δϕ=0.1° for the input circuit and Δϕ=0.9° for the output circuit. The resonance frequency of the sensor installed in column 1 (Fig. 1) was 5869.25 Hz. Measurements of the oscillation frequency were carried out for three values of the feedback transmission coefficient.

Table 1

Results of definition of absolute error

Resonance frequency	Absolute error, Hz		
	K=1.00	K=0.65	K=0.35
F_p=5869.25 Hz	1.25	0.98	0.84

The obtained values of the absolute error make it possible to use the vibrofrequency method to control the frequency-modular oscillations of the contacting phases.

6. Discussion of the results of investigation of the effect of magnetic and electric fields

Influence of electric and magnetic fields on intensification of heat and mass exchange processes in liquid systems with submersible combustion devices has not been investigated before.

The results of the research make it possible to use electric and magnetic fields in gas-liquid systems as a means of intensifying the process of heat and mass transfer and improving the energy efficiency of the submersible combustion devices. This is confirmed by the dependences of the mass transfer coefficients on the characteristics of electric and magnetic fields.

However, a comparative analysis of the results of intensification of mass-exchange processes in gas-liquid systems indicates that the optimal method of action is the method of inducing oscillations in the zone of contacting phases due to an electric spark discharge. The discharge occurs when constant or alternating electrical potentials are applied to the electrodes located in the phase interaction zone.

Generation of discrete electrical discharges between the electrodes leads to an electro-hydraulic effect in the contacting phases. The resulting effect causes phase pulsations, cavitation, magnetic, electric, acoustic and light phenomena. The listed phenomena, ultimately, result in an increase in the speed of the mass transfer process. By changing the shape, location of the electrodes, the distance between them, as well as the magnitude of the electrodes, polarity and frequency of supplied electrical potentials, it is possible to accelerate or slow down the process of phases contacting.

The proposed vibrofrequency method for controlling electro-hydraulic effect of the heat and mass transfer process can be widely used in automation of submerged combustion devices. The control method allows one to neglect measurements of pressure and temperature of each phase, speed characteristics of flows, characteristics of magnetic and electric fields causing oscillations of contacting phases. The effects arising from the action of magnetic and electric fields are estimated by measuring the oscillation frequency of the contacting gas-liquid phases.

7. Conclusions

1. Influence of electromagnetic fields imposed on the gas-liquid interface on intensification of heat and mass transfer was established. The coefficients of mass transfer as a function of intensity of electromagnetic fields were determined.

2. It was established that when electric field is applied to gas-liquid contacting phases in installations equipped with SCD, intensity of mass transfer increases. It is shown that magnetic fields characterized by small intensities can be used to intensify mass-exchange processes.

3. The optimal way to intensify heat and mass transfer in reactors equipped with submersible combustion devices is to create oscillations of the contacting phases at the interface between them by an electric spark discharge that appears when electric potentials are applied to the electrodes.

4. A method for controlling forced oscillations of contacting gas-liquid phases using the developed vibrofrequency measuring transducer with a cylindrical resonator was proposed. The advantage of the proposed vibration control method is absence of the need to measure characteristics of the magnetic and electric fields that affect the contacting phases. At the same time, the resulting of fields on the gas-liquid layer was estimated.

References

1. Kuzma-Kitcha, Yu. A. Metody intensifikacii teploobmena [Text] / Yu. A. Kuzma-Kitcha. – Moscow: Izd-vo MEHI, 2001. – 112 p.
2. Ibragimov, U. H. Intensifikaciya teploobmena v kanalah [Text] / U. H. Ibragimov, S. M. Shamuratova, B. A. Rahmonov // Molodoy uchenyy. – 2016. – Issue 8. – P. 225–229.
3. Tovazhnyanskiy, L. L. Osnovy ehnergotekhnologii promyshlennosti [Text] / L. L. Tovazhnyanskiy, O. B. Anipko, V. A. Malyarenko, Yu. A. Abramov, V. I. Krivcova. – Kharkiv: NTU “HPI”, 2002. – 436 p.
4. Nikolsky, V. Development and study of contact-modular heating system using immersion combustion units [Text] / V. Nikolsky // Eastern-European Journal of Enterprise Technologies. – 2015. – Vol. 4, Issue 8 (76). – P. 31–35. doi: 10.15587/1729-4061.2015.47459
5. Noghrehabadi, A. Effect of magnetic field on the boundary layer flow, heat, and mass transfer of nanofluids over a stretching cylinder [Text] / A. Noghrehabadi, M. Ghalambaz, E. Izadpanahi, R. Pourrajab // Journal of Heat and Mass Transfer Research. – 2014. – Vol. 1, Issue 1. – P. 9–16.
6. Gusbeth, C. Pulsed electric field treatment for bacteria reduction and its impact on hospital wastewater [Text] / C. Gusbeth, W. Frey, H. Volkmann, T. Schwartz, H. Bluhm // Chemosphere. – 2009. – Vol. 75, Issue 2. – P. 228–233. doi: 10.1016/j.chemosphere.2008.11.066
7. Miao, X. Effect of an Electromagnetic Brake on the Turbulent Melt Flow in a Continuous-Casting Mold [Text] / X. Miao, K. Timmel, D. Lucas, Z. Ren, S. Eckert, G. Gerbeth // Metallurgical and Materials Transactions B. – 2012. – Vol. 43, Issue 4. – P. 954–972. doi: 10.1007/s11663-012-9672-0
8. Vogt, T. An experimental study of a bubble-driven liquid metal flow under the influence of a rotating magnetic field [Text] / T. Vogt, A. Andruszkiewicz, S. Eckert, K. Eckert, S. Odenbach, G. Gerbeth // Journal of Iron and Steel Research International. – 2012. – Vol. 19. – P. 505–508.
9. Kang, Y. Reaction process under the influence of an electromagnetic field [Text] / Y. Kang // Transactions of Nonferrous Metals Society of China. – 2016. – Vol. 26. – P. 1439–1446.
10. Zhao, L. Simulation of Magnetic Resonance for Wireless Power Transfer [Text] / L. Zhao, Y. Liu // Research Journal of Applied Sciences, Engineering and Technology. – 2013. – Vol. 5, Issue 05. – P. 1578–1582.
11. Yan, H. Pull-In Effect of Suspended Microchannel Resonator Sensor Subjected to Electrostatic Actuation [Text] / H. Yan, W.-M. Zhang, H.-M. Jiang, K.-M. Hu // Sensors. – 2017. – Vol. 17, Issue 1. – P. 114. doi: 10.3390/s17010114
12. Etkin, L. G. Vibrochastotnye datchiki. Teoriya i praktika [Text] / L. G. Etkin. – Moscow: MGTU im. N. E. Baumana, 2004. – 408 p.

13. Zhang, W.-M. Dynamics of Nonlinear Coupled Electrostatic Micromechanical Resonators under Two-Frequency Parametric and External Excitations [Text] / W.-M. Zhang, G. Meng, K.-X. Wei // Shock and Vibration. – 2010. – Vol. 17, Issue 6. – P. 759–770. doi: 10.1155/2010/107404
14. Oliynyk, O. Development of autooscillating system of vibration frequency sensors with mechanical resonator [Text] / O. Oliynyk, Y. Taranenko, A. Shvachka, O. Chorna // Eastern-European Journal of Enterprise Technologies. – 2017. – Vol. 1, Issue 2 (85). – P. 56–60. doi: 10.15587/1729-4061.2017.93335
15. Nikolsky, V. The development and study of immersed burning apparatus with multiple phases inversion [Text] / V. Nikolsky // Technology audit and production reserves. – 2015. – Vol. 4, Issue 1 (24). – P. 60–64. doi: 10.15587/2312-8372.2015.47791
16. Agaev, A. A. Issledovanie absorbcii gazov v ehlektricheskom pole [Text] / A. A. Agaev, V. I. Ibragimov, T. S. Kurbanaliev // Uchenye zapiski Azerb. Instituta nefti i himii. – 1976. – Issue 5. – P. 45–50.
17. Dul'nev, G. N. Teoriya teplo- i massoobmena [Text] / G. N. Dul'nev. – Sankt-Peterburg: NIU ITMO, 2012. – 195 p.
18. Gonoskov, I. A. Ionizaciya k kvantovannom ehlektromagnitnom pole [Text] / I. A. Gonoskov, G. A. Vugal'ter, V. A. Mironov // Zhurnal ehksperimental'noy i teoreticheskoy fiziki. – 2007. – Vol. 132, Issue 6. – P. 1278–1290.
19. Karasevich, Yu. K. Kinetika himicheskoy ionizacii v udarnyh volnah [Text] / Yu. K. Karasevich // Kinetika i kataliz. – 2009. – Vol. 50, Issue 2. – P. 163–169.
20. Kunova, O. V. Vliyanie neravnovesnoy kinetiki na teploperenos i diffuziyu za frontom udarnoy [Text] / O. V. Kunova, M. A. Mekhonoshina // Fiziko-himicheskaya kinetika v gazovoy dinamike. – 2014. – Vol. 15, Issue 1.
21. Sister, R. G. Principy povysheniya ehffektivnosti teplomassoobmennyh processov [Text] / R. G. Sister, Yu. V. Martynov. – Kaluga: Izd-vo Bochkarevoy N, 1998. – 507 p.
22. Molchanov, A. D. Metod iskrovyh razryadov dlya uskoreniya massoobmena v sisteme tverdoe telo-zhidkost' [Text] / A. D. Molchanov, A. G. Aksel'rud, A. I. Chernyavskiy et. al. // IFZH. – 1970. – Vol. 18, Issue 2. – P. 293 299.
23. Prisnyakov, V. Teplomassoobmen i vibraciya [Text]: monografiya / V. Prisnyakov, S. Bondarenko, V. Lucenko et. al. – Odessa: Neptun-Tekhnologiya, 2001. – 208 p.