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MASSTRANSFER FEATURES IN THE APPARATUSES WITH A MOVING NOZZLE IN A THREE-PHASE FOAM LAYER

The improvement of heat and mass exchange equipment for sorption processes in the countercurrent contact of gas and liquid in combined block elements with a weighted spherical nozzle, as well as a more in-depth study of this process, is an urgent task of chemical technology. A fundamentally new type of ball-shaped three-dimensional mesh fluidized nozzle was developed and researched, the bodies of which are made of polymer layers with holes, and a freely coiled metal or polymer mesh is located inside. The nozzle has a high specific surface area, developed free volume and low bulk density. The study of mass transfer in the liquid and gas phases was carried out and the corresponding calculation equations were obtained. Dependencies for the calculation of the mass transfer coefficients and the efficiency of the combined block element on the mode and design parameters are established. The results of calculations based on the obtained dependencies show a sufficient correlation with the experimental data. The proposed model of the desorption process of carbon dioxide from water, which allows predicting the values of the efficiency indicators of the decarbonization process. It was established that the use of a combined block element with a ball-shaped nozzle allows to increase the mass transfer coefficients compared to the failure plate. The industrial implementation of absorption processes in the foam layer and the use of the gas-liquid layer stabilization method significantly expands the scope of application of foam apparatuses and opens up new opportunities for intensifying technological processes. Previously expressed assumption about the perspective of using mesh materials for the manufacture of nozzle bodies was confirmed by experiments, but the peculiarity of the operation of devices with similar nozzles should be emphasized.

***Keywords**: process engineering and design; masstransfer; combined block element; intensive apparatus; three-phase interaction; perforated plate; turbulation; moving nozzle; decarbonization; absorption and desorption processes; carbon dioxide*

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ОСОБЛИВОСТІ МАСООБМІНУ В АПАРАТАХ З РУХОМОЮ НАСАДКОЮ В ТРИФАЗНОМУ ПІННОМУ ШАРІ

Удосконалення тепломасообмінного обладнання для сорбційних процесів при протитечійному контакті газу і рідини в комбінованих блочних елементах з обваженою сферичною насадкою, а також більш поглиблене дослідження цього процесу є актуальним завданням хімічної технології. Розроблено та досліджено принципово новий тип кулястої тривимірної сітчастої псевдозрідженої насадки, корпуси якої виконані з шарів полімеру з отворами, а всередині розташована вільно навита металева або полімерна сітка. Насадка має високу питому поверхню, розвинений вільний об'єм і низьку насипну густину. Проведено дослідження масообміну в рідкій і газовій фазах та отримано відповідні розрахункові рівняння. Встановлено залежності для розрахунку коефіцієнтів масовіддачі та ефективності комбінованого блочного елемента від режимних і конструктивних параметрів. Результати розрахунків за отриманими залежностями показують достатню кореляцію з експериментальними даними. Запропонована модель процесу десорбції діоксиду вуглецю з води, яка дозволяє прогнозувати значення показників ефективності процесу декарбонізації. Встановлено, що використання комбінованого блочного елемента з кулеподібною насадкою дозволяє підвищити коефіцієнти масопередачі в порівнянні з провальною тарілкою. Промислова реалізація процесів абсорбції в пінному шарі та використання методу стабілізації газорідинного шару значно розширює сферу застосування пінних апаратів і відкриває нові можливості для інтенсифікації технологічних процесів. Раніше висловлене припущення про перспективність використання сітчастих матеріалів для виготовлення корпусів насадок підтвердилося експериментами, але слід підкреслити особливість роботи апаратів з подібними насадками.

***Ключові слова:** технологічне проектування та дизайн; масообмін; комбінований блок-елемент; інтенсивний апарат; трифазна взаємодія; перфорована тарілка; турбулізація; рухома насадка; декарбонізація; процеси абсорбції та десорбції; вуглекислий газ*

Introduction. Heat and mass transfer processes between gas and liquid are widely used in the chemical, oil refining, and energy industries. One of the promising directions of intensification of the mass transfer process is the development of devices using the principle of interaction of gas-liquid flows in a layer of moving bodies, so-called foam devices with a three-phase fluidized layer of an irrigated nozzle.

Compared to traditional plate and packed columns, foam devices with a three-phase fluidized bed have the following advantages:

- the possibility of working in a wide range of gas velocities without a significant increase in hydraulic resistance, which is especially important for gas purification processes in conditions with frequently changing flow velocities, both decreasing and increasing;
- practically uniform distribution of the liquid phase over the entire cross-section of the apparatus and complete washing of the surface of the nozzle with liquid, which leads to an increase in the mass exchange surface;
- turbulence of gas and liquid flows, which ensures high heat and mass transfer coefficients;
- the possibility of intensifying the work of absorption columns equipped with falling plates by using fluidized nozzles.

The modern trend is to combine and combine plate and plug contact devices in one device. To increase the productivity of columns sectioned by plates, drop-type plates with a large free cross-section are used. However, such plates have low efficiency because they work at large values of splashing. In order to reduce the impact of splashing on the efficiency of the plate, in addition to the weighted nozzle, separators of a special design are placed in the separation space between the failed plates, which work as stabilizers of the three-phase foam layer when the apparatus is operating in the advanced bubbling mode [1].

Current status of the problem. There are also reports in the literature about laboratory studies of devices with a fluidized bed of an irrigated nozzle of various configurations. For example, spherical nozzles were tested in works [2]. The work [3] describes nozzles in the form of rings. In the following years, research was conducted mainly on the ball nozzle, as it is the simplest in terms of design and manufacturing method. Such studies are described in works [4].

Different designs of devices with a three-phase layer of irrigated nozzle are known, which differ in the type of nozzle and the nature of its movement, in the design of the support and distribution grid, which holds the grid, nodes for supplying gas, liquid, etc [5].

Apparatuses with a three-phase layer are divided into apparatuses with cross-flow, counter-flow and upward direct-flow movement of phases according to the organization of movement of gas and liquid flows on the plate.

In work [4], the nature of the movement of the nozzle bodies in the working volume is the basis for the classification of countercurrent devices with a fluidized bed of the irrigated nozzle; according to which devices with a weighted nozzle, with a gushing nozzle, with a rotating nozzle and a circulating nozzle, with a regular moving nozzle and combined devices with a moving nozzle are distinguished.

Devices with a weighted nozzle [5] differ from others in the chaotic and pulsating nature of the movement of nozzle elements in a suspended state. Apparatus with a weighted nozzle can be sectionalized, that is, they use different partitions, inserts, stabilizers or grids of large free cross-section, which divide the cross-section of the apparatus and its working area into separate sections. In such devices, the issue of a large-scale transition from laboratory models to industrial columns is successfully solved without a particular change in the efficiency of mass and heat exchange.

Devices with a jet nozzle use zigzag or conical plates. In devices with a gushing nozzle with zigzag-shaped plates, the gushing of the nozzle occurs in the central part of each zigzag. To prevent accumulation of the nozzle in the depressions of zigzags, the perforated part of the plate can be made in the form of a perforated or slotted horizontal plate.

The basis of devices with a circulating nozzle and a rotating nozzle [6] is the circulating or rotary movement of the nozzle, which is organized with the help of additional paths, various methods and special devices.

In the working area of devices with a circulating nozzle, there is an upward movement of the nozzle, which returns to the grid through external transport paths or internal zones in the device body. The rotation of the nozzle is carried out in different ways in the working area of the device. One of them is a gas stream pre-swirled by means of directional grid nozzles.

In other cases, upper limiting grids or reflectors in the form of hemispheres, perforated inclined plates, etc. are used, which give the nozzles a rotational movement.

Devices with gushing and circulating nozzles work at high gas velocities and have high hydraulic resistance.

In devices with a regular movable nozzle, nozzle bodies can be freely mounted on rigid strings or, on the contrary, rigidly fixed on flexible strings. In the first case, the strings are stretched between the walls of the case or between the bars, the nozzle moves only along the string; at the same time, the run of each nozzle element along the string is limited. Flexible strings with a rigidly fixed regular movable nozzle are cantilevered to the wall of the device or to the bars.

A common design of the nozzle, in which one end of the string with the nozzle is fixed from above to the mounting grid, and the other end is freely passed through the opening of the distribution grates. The elasticity or flexibility of the strings allows the nozzle elements to perform transverse and longitudinal oscillating movements under the influence of the currents.

Regular movable nozzles are difficult to operate and work with increased gas loads.

Combined devices with a moving nozzle are even more complex designs that combine elements of fluidized bed and bubble devices.

The most common in industry are devices with a weighted fluidized nozzle, which are structurally simpler and can be improved in the direction of reducing energy consumption, which is important for gas purification processes [7].

Currently, in order to reduce the energy costs for carrying out the mass transfer process, it is advisable to use packing bodies made of foamed and mesh materials [8], since these materials make it quite easy to manufacture packing bodies with a highly developed phase contact surface, which at the same time have a low bulk density, which is confirmed studies presented in the work [9]

A new design of a stabilizer with a large free volume and a movable spherical nozzle was developed [1]. The advantage of the proposed design is the transition to a structured foam mode of operation at relatively low gas speeds, as well as a developed inner phase contact surface. The cellular structure of the stabilizer and movable nozzle makes it possible to achieve increased values of mass transfer coefficients due to the effect of film formation in small cells. The structure has high porosity and relatively low hydraulic resistance.

Placed between the dip plates, the stabilizers themselves are an additional phase contact zone. For stable operation in combination with drop-type plates of a large free section and a weighted nozzle, the design of the stabilizer must allow high gas and liquid performance, have relatively small hydraulic resistance and have good separation characteristics.

A fundamentally new three-dimensional spherical hollow nozzle was also developed, the advantage of which is the transition to a fluidized state at relatively low gas velocities, as well as a developed surface of phase contact both in a stationary position and in dynamic mode. The cellular structure from which the nozzle is made allows to achieve increased values of mass transfer coefficients due to the effect of film formation in small cells [10]. The nozzle has a high porosity and relatively low hydraulic resistance. Depending on the selection of material, the nozzle can have different wettability.

The new movable nozzles are simple in design and have a relatively low cost, which allows them to be effectively used in absorption-desorption processes, including for the purification of gases from various industries, in cooling towers and for decarbonization in circulating water and heat supply systems, in a number of other heat processes - and mass exchange.

The section of the column apparatus has a wide working range, and is a combination of a mass exchange plate with a movable spherical nozzle in combination with a stabilizer of the foam layer, which is also a separator that reduces splashing between sections [11].

Such a combined block element with a weighted spherical nozzle and a stabilizer can work at high velocities of both gas and liquid phases, which allows increasing the productivity and efficiency of mass transfer columns. In devices with similar combinations of contact devices, higher values of mass transfer coefficients can be obtained with lower specific energy consumption, which determines their high energy efficiency. At the same time, the hydrodynamic and mass transfer processes for such sections in active hydrodynamic regimes have not been sufficiently studied, and there are no methods of their engineering calculation in the literature [12].

Research methodology. A new design of the stabilizer with a large free volume and spherical nozzles was developed. The advantage of the proposed design is the transition to a structured foam mode of operation at relatively low gas velocities, as well as a developed phase contact surface. The cellular structure of the stabilizer and the nozzle makes it possible to achieve increased values of mass transfer coefficients due to the effect of film formation in small cells. The structure has high porosity and relatively low hydraulic resistance. Depending on the material selection, the structure can have different wettability. The new designs are simple and have a relatively low cost, which allows them to be effectively used in the processes of purification of waste gases in various industries, in cooling towers of recycled water supply systems, in a number of other heat and mass transfer processes, including by modernizing existing plants.

To study the hydrodynamic parameters, contact elements were selected - stabilizers, which are packages or blocks assembled from steel flat and corrugated sheets of metal mesh at an angle of 30, 45, 60, 90°.

The combined contact block consists of a hole plate and one or two contact elements acting as stabilizers, and a movable ball-shaped nozzle located inside the block. The bubbling layer is formed on hole plates on which a movable nozzle is located. The design features and operating modes allow the system to self-clean from possible dispersed inclusions and operate for a long time without stopping for cleaning. The new designs are simple and have a relatively low cost, which allows them to be effectively used in the processes of gas cleaning in various industries. The most suitable way to study mass transfer in the liquid phase is studying the process of desorption of CO_2 from a saturated liquid into an air stream. The methodology of such a study is fully presented in the work [13]. Experimental installation for gas-phase mass transfer is shown on Figure 1.

To monitor the mass yield in the gas phase, ammonia was collected in the container of the absorbed component, and water was collected in the clay container. The air looked like an inert gas that does not dissolve in the water. A combined block element 2 is located inside the column 1. An air-ammonia mixture was supplied from the bottom of the column, which was obtained by mixing ammonia from the cylinder 12 with air pumped by the gas blower 5. Irrigation water was supplied to the top of the column from the water supply system through a liquid distributor. Ammonia water of weak concentration, formed as a result of absorption, was discharged into the sewer, and the air was discharged into the atmosphere. The consumption of water and ammonia was regulated by valves 9 and measured, respectively, by rotameters 8.

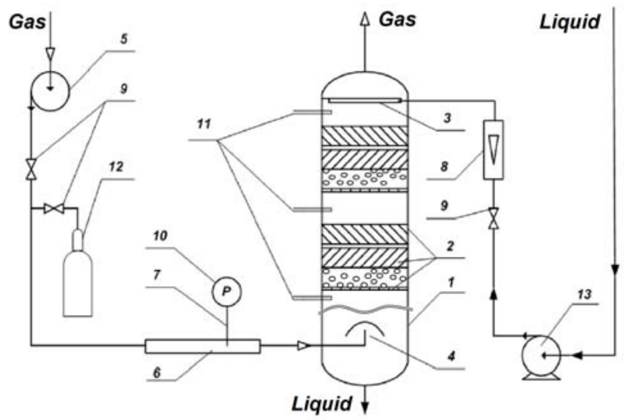

Figure 1 – Experimental equipment setup for studying mass transfer in the gas phase
1 – column; 2 – combined contact element block; 3 – liquid distributor; 4 – gas distributor; 5 – gas blower; 6 – measuring pipe; 7 – Pitot tube; 8 – rotameter; 9 – valves; 10 – diffmanometer; 11 – samplers; 12 – ammonia cylinder; 13 – pump

The mass yield in the gas phase was studied on a stand with a 0,24 m column under the conditions of ammonia absorption by water. Ammonia absorption was carried out at a gas velocity = 1 - 5 m/s using the stabilization of a three-phase foam layer on perforated plates with a weighted spherical nozzle. Liquid consumption was from 1 to 15 $m^3/m^2 \cdot h$. The stabilizer was installed above the canvas of the perforated plate at a height of 0,30 m.

Ammonia was determined by sampling followed by titration. The sampling procedure was carried out as follows: the water supply valve was opened and the required flow rates were set. Then the gas blower was started and the air flow was set, which corresponded to the visual foam mode. Valve 9 was opened for ammonia supply and its consumption was set. After 5 minutes, gas samples were taken at the bottom and top of the column and a liquid sample at the bottom of the column. The temperature of the medium was 20°C. Then the sampling was repeated again. At the end of the measurements, the ammonia supply was closed, the gas blower was turned off, and the water was shut off. The experiment was performed at atmospheric pressure. The ammonia in the sample was determined according to the method [14] using phenolphthalein, sulfuric acid solution, and sodium hydroxide solution. The costs and amount of absorbed ammonia were determined by the material balance of absorption [15].

Research results. Effective operation of mass transfer devices is achieved with a certain combination of values of the mass transfer coefficient K and the efficiency coefficient η, which characterizes the efficiency of the process.

The research of mass transfer in the gas phase was presented in [13] by the propose of a mathematical model for calculating the efficiency of CO_2 extraction from water, and to perform calculations of new nozzles for which there is no experimental data on the effectiveness of decarbonization.

During the research of mass transfer in the gas phase, patterns of ammonia absorption from the main parameters of the experiment were revealed: gas velocity in the cross-section of the column, ammonia concentration, free cross-section of the perforated plate, loads on the liquid.

During experiments on ammonia absorption Figure 2, it was found that the efficiency of the apparatus depends on the change in gas velocity.

The efficiency coefficient is significantly higher when using stabilization with a plate with a smaller free cross-section, such a plate has a greater hydraulic resistance. This can be explained by the fact that plates with a smaller free cross-section contribute to a greater retention of liquid on the plate, as well as the formation of a higher height of the three-phase layer, increasing the mass transfer surface.

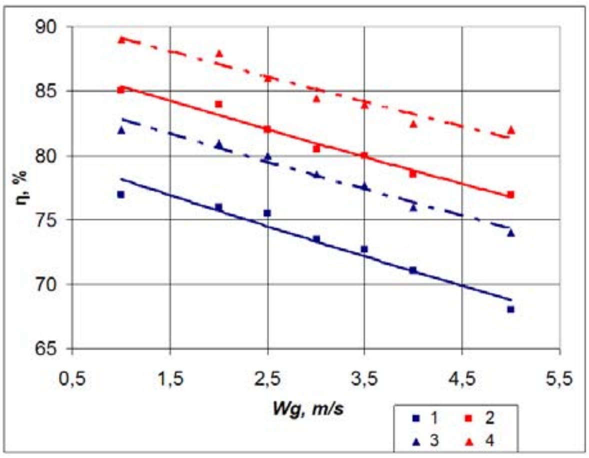

Figure 2 – Dependence of the efficiency factor for the ammonia-water system in a combined block element with a spherical nozzle on the gas velocity
$L_0 = 5$ m^3/m^{2}h; 1 – $S_0 = 0,217$ m^2/m^2 (first modification); 2 – $S_0 = 0,137$ m^2/m^2 (first modification); 3 –$S_0 = 0,217$ m^2/m^2 (second modification); 4 – $S_0 = 0,137$ m^2/m^2 (second modification)

After considering the experimental data presented in Figbre 3 it can be stated that an increase in the free cross-sectional area leads to a decrease in the efficiency of the block element.

From Figure 4 it can be seen that the irrigation density has an effect on absorption only up to 10 m^3/m^{2}h, then its effect stabilizes and does not increase significantly. When installing the stabilizer, the values of the coefficient of useful action in the combined block element with a weighted spherical nozzle were observed to stabilize even when the concentration of ammonia changed Figure 5. Such a dependence of the efficiency coefficient confirms the proposition about the efficiency of the proposed design when changing the technological modes of the equipment, and makes it possible to use known methods for calculating the number of stages to achieve the given efficiency of the process.

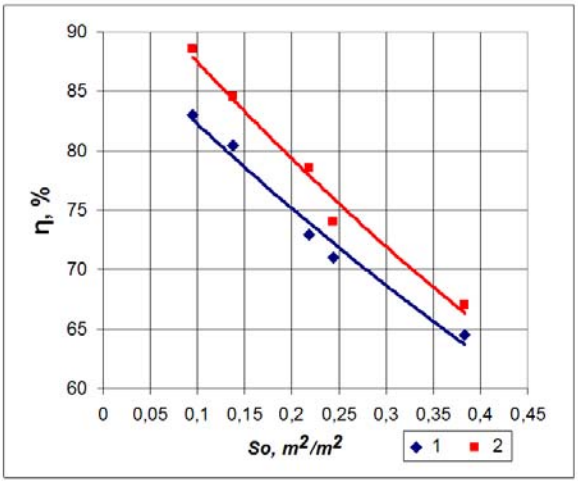

Figure 3 – Dependence of the efficiency factor in the ammonia-water system in the combined block element with a weighted spherical nozzle on the free cross-section of the perforated plate Wg = 3 m/s, $L_0 = 5$ m^3/m^{2}h, concentration of NH_3 = 2%. 1 – the first modification of the nozzle, 2 – the second modification of the nozzle

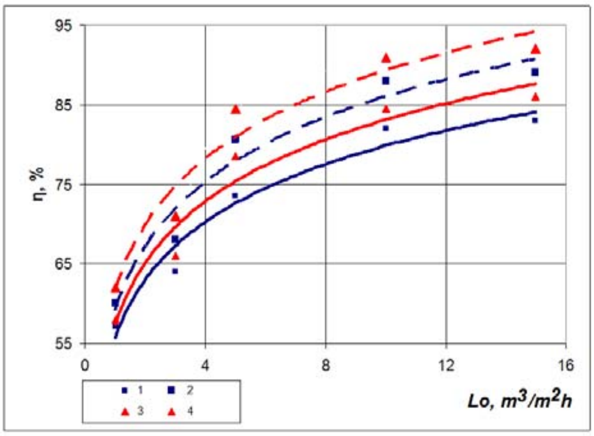

Figure 4 – The dependence of the efficiency coefficient for the ammonia-water system in the combined block element on the irrigation density

Wg = 3 m/s, concentration of NH_3 = 2%: 1 – S_0 = 0,217 m^2/m^2, 2 – S_0 = 0,137 m^2/m^2 (the first modification of the nozzle); 3 – S_0 = 0,217 m^2/m^2, 4 – S_0 = 0,137 m^2/m^2 (the second modification of the nozzle)

So, after analyzing Figure 6 it can be said that an increase in liquid irrigation increases the mass transfer coefficient. When the free cross-sectional area of the perforated plate increased Figure 7, a decrease in the ammonia absorption coefficient was observed. This can be explained by a decrease in the amount of liquid in the combined block element, a greater drop of liquid to the lower contact stages and a decrease in the contact surface of the phases.

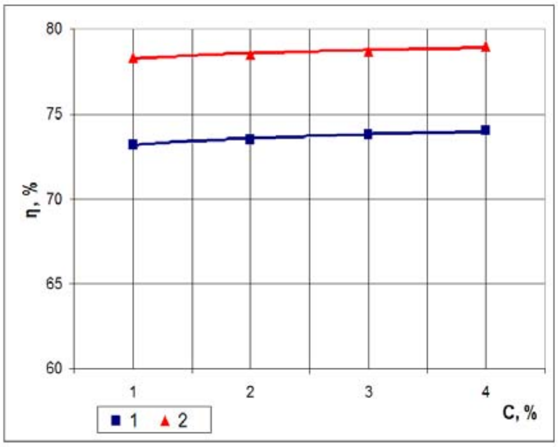

Figure 5 – Dependence of the efficiency coefficient for the ammonia-water system in a combined block element with a weighted spherical nozzle depending on the ammonia concentration

Wg = 3 m/s, L_0 = 5 m^3/m^2h; S_0 = 0,217 m^2/m^2: 1 – the first modification of the nozzle; 2 – the second modification of the nozzle

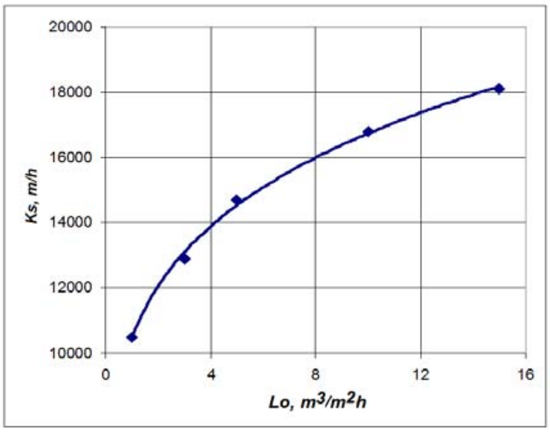

Figure 6 – Dependence of the mass transfer coefficient related to the area of the plate on the irrigation density on the combined block element with a spherical nozzle (second modification) Ammonia – water system, S_0 = 0,137 m^2/m^2, Wg = 3 m/s

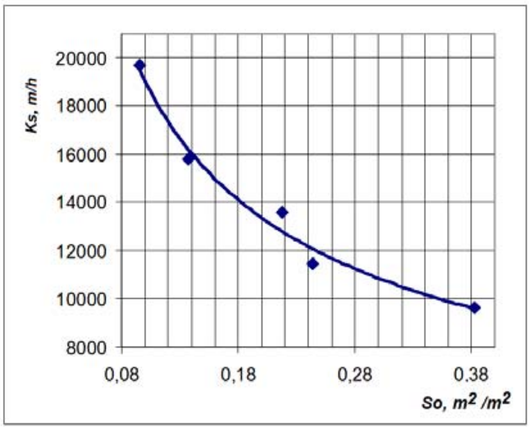

Figure 7 – Dependence of the mass transfer coefficient related to the area of the plate on the free cross-section of the perforated plate when using the nozzle of the second modification Ammonia – water system: L_0 = 5 m^3/m^2h, Wg = 3 m/s.

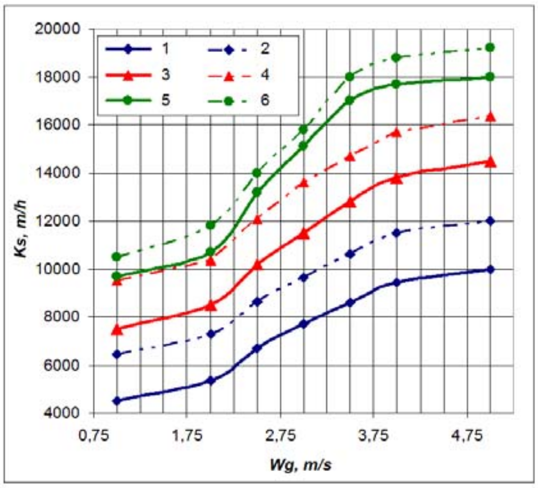

Figure 8 – Dependence of the mass transfer coefficient of the combined block element with a weighted spherical nozzle on the gas velocity
Ammonia – water system: L_0 = 5 m^3/m^2h; 1, 3, 5 – the first modification of the nozzle, 2, 4, 6 – the second modification of the nozzle; 1, 2 – S_0 = 0,383 m^2/m^2; 3, 4 – S^0 = 0,137 m^2/m^2; 5, 6 – S_0 = 0,217 m^2/m^2

As can be seen from Figure 8 gas velocity has a significant effect on the height of the gas-liquid layer and the mass transfer coefficient in the combined block element.

After processing the experimental data, empirical dependences were obtained for calculating the mass transfer coefficient in the gas phase m/h:

$$K_s = 1600 \cdot W_g^{1,5} L_0^{0,12} S_0^{-0,72} \quad (1)$$

and when determining the efficiency, %:

$$\eta = 715 \cdot W_g^{-1,75} L_0^{0,3} K_s^{1,25} \quad (2)$$

Formulas are used within the following limits: W_g = 1 - 5 m/s, L_0 = 1 - 15 m^3/m^2h, S_0 = 0.09 - 0.4 m^2/m^2. The error of calculations based on these equations did not exceed 15%.

So, the previously expressed assumption about the perspective of using mesh materials for the manufacture of nozzle bodies was confirmed by experiments, but the peculiarity of the operation of devices with similar nozzles should be emphasized.

Therefore, the mass transfer process, both in the gas and liquid phases, is significantly influenced by hydrodynamic parameters - the gas velocity in the apparatus and the specific load on the liquid, which indirectly affect the height of the liquid layer on the plate and the gas content of the layer, as well as physical chemical properties of interacting systems [16, 17].

Conclusions. A promising direction for intensifying absorption/desorption processes is the development of devices with a three-phase stabilized pseudo-liquefied layer of an irrigated movable nozzle made of mesh materials. For gas purification systems for gaseous components, it is necessary to ensure low liquid loads while maintaining a high degree of purification. This can be achieved by using a slump plate with a small or medium free cross-section and a newly developed spherical nozzle and stabilizer when the device operates in an advanced foam mode with stabilization.

The analysis of a number of studies [2-6, 7, 9] shows that a promising direction for intensifying the mass transfer process is the development of devices with a three-phase fluidized bed of irrigated nozzles of complex shapes made of mesh materials. For gas purification systems from gaseous components, it is necessary to ensure low fluid loads while maintaining a high degree of purification. This can be achieved by using a slump plate with a small free cross-section and a newly developed nozzle.

The increase in the number of diverse and complex emissions into the atmosphere, which accompanies the growth of a number of industries, creates a need for efficient and reliable gas treatment plants [18].

The intensification of foam devices has become possible thanks to the use of new designs with a foam layer stabilizer. The wave mode does not occur on the stabilizer grids, so the gas velocity in the full cross-section of the unit can be more than doubled and reach 5 m/s. Elimination of the foam layer oscillations leads to a significant increase in the height of the foam and the outlet liquid layer, and the degree of poorly soluble gases capture increases over the entire range of gas velocities studied.

The range of stable operation of the devices under changes in gas and liquid loads is significantly expanded. This is crucial for the reliable and efficient operation of gas cleaning systems of technological lines with variable power load.

The industrial implementation of absorption processes in the foam layer and the use of the gas-liquid layer stabilization method significantly expands the scope of application of foam apparatuses and opens up new opportunities for intensifying technological processes. The use of modern designs of movable nozzles in combination with foam layer stabilizers makes it possible to modernize existing technological installations. At the same time, it is possible to simultaneously create low-waste technologies.

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