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PROCESSES AND EQUIPMENT OF CHEMICAL INDUSTRY

Research of the Heat and Mass Exchange Features of Gas Saturation into Gas–Liquid Apparatus with High-Speed Agitator in a Flow Circuit

D. S. Pashkevich, P. S. Kambur, D. A. Mukhortov, V. B. Petrov, and Yu. I. Alekseev

Russian Scientific Center "Apllied Chemistry", St. Petersburg, Russia

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Abstract—The saturation of a liquid phase with a gas and the heat exchange in a gas-liquid apparatus with a high-speed agitator in a flow circuit at various operating modes, constructions of the agitators were investigated and under various physical conditions.

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Physicochemical and biological transformations in the heterogeneous systems gas–liquid are of widest applied in different technological processes. The development of the corresponding reaction equipment, the calculation methods of whose problems of chemical kinetics, hydrodynamics, heat and mass exchange are the inherent condition of the successful realization of these processes in the industry.

The kinetics of gas–liquid reactions and the mathematical simulation of chemical reactors is in sufficient detail described in the literature. However, hydrodynamic phenomena in the interaction of gas and the liquid, the convective heat exchange between the gas–liquid mixture and the walls of heat exchange elements, and mass transfer in the heterogeneous systems being decisive factors in the generalized form and with the necessary theoretical prerequisites in the open literature are not represented fully, and for all types of apparatuses.

A maximum increase in heat-transfer coefficient from the flow to the wall of apparatus which is attained by the use of gas–liquid reactors with the mechanical agitation is required for performing the high exothermic processes in the gas–liquid systems. An apparatus with the flow circuit that looks like a pipe axially symmetrical with the reactor body, and where is placed an agitator, is one of the types of gas–liquid reactors with the mechanical agitation. In this apparatus the spiral regulated motion of the liquid along the closed outline where the liquid moves from bottom to top inside the circulation pipe while in radial clearance between the circulation pipe and the reactor body, in the opposite direction. The dispersion of gas occurs in the agitator area (due to the direct effect of its blades on the gas bubbles) and as well as due to the turbulent pulsations of the liquid.

In such apparatus design the heat exchange elements can be both the vessel walls and the circulation pipe made of pipes fixed in the ring-like position connected with each other by tie plates [1].

The apparatus of such design has still several advantages. First, the formation of the axial funnel of liquid is excluded. On the other hand, it is possible to introduce reactive gases into the divided volumes of the reactor ensuring the dispersion of gas flows before their direct contact that prevents the formation of large gas bubbles. This is especially urgent when conducting fluorination of gaseous compounds in the liquid by elemental fluorine [2].

The time of the contact of liquid and gas is one of the basic parameters which determines the efficiency of the gas–liquid apparatus. For the apparatuses with the high-speed mixers this parameter is determined not by the time of the emersion of bubble but by the ability of the moving

flow to retain bubble due to the inertia. In this case the time of contact is calculated experimentally. The ratio of the volume of the gas phase concluded in the volume of the liquid to the volume of the gas–liquid mixture is considered as the true gas content φ of the system.

In the contemporary literature there is no information on experimental data or theoretical dependences for determining the gas content φ and the heat-transfer coefficient α for the gas–liquid reactors with the agitator in the circulation pipe.

It is known from literature data that for the gas–liquid reactors with the agitator the gas content of the liquid φ depends on different parameters thereby the frequency of the agitator rotation, the agitator diameter, and submersion depth into the liquid, the liquid viscosity, the gas flow are governing. For the gas–liquid apparatus with the agitators in the free volume there are empirical dependence for computation of the value of the gas saturation and the heat transfer coefficient from the flow of gas–liquid mixture to the wall for many types of agitators and different constructions of apparatuses [1, 3, 4].

Thus, for the gas–liquid agitator in the free volume the maximum value of gas saturation comprises 16% [3]. The value of the gas saturation is computed for the apparatus with six baffles with the use of a four-blade agitator. The frequency of rotation is 35 Hz, the volume of apparatus, 10 l. The water was used as the liquid medium, air, as the gas. A feature of the dependences of the value of the gas saturation on the frequency of the rotation of the agitator was not given in [3].

Experimental studies on the laboratory setup were carried out for determining the influence of the above-mentioned parameters on φ in the apparatus with the high-speed agitator in the circulation pipe.

The scheme of the apparatus with the high-speed mechanical agitator in the flow circuit is depicted in Fig. 1. The reactor is cylindrical container *1* with a height of 333 mm and with a diameter of 73 mm supplied with a high-speed agitator and internal circulation pipe with a height of 300 mm and with a diameter of 52 mm; the six blade turbine agitator with the slope of the blades *2* equal to 45°C, is located on shaft *3* inside the circulation pipe *4*. An inlet *5* serves for the gas feed to the reactor. A vessel *6* serves for the separation of the gas–liquid mixture and gas outlet. The shaft *3* was sealed with the aid of the stuffing-box seal. Heating electric circuit *7* and refrigerator *8* provided changing the temperature of the gas–liquid mixture. The measurement of the temperature of the gas–liquid medium was performed by two thermocouples with protected surface, the measurement of the wall temperature, by two external thermocouples.

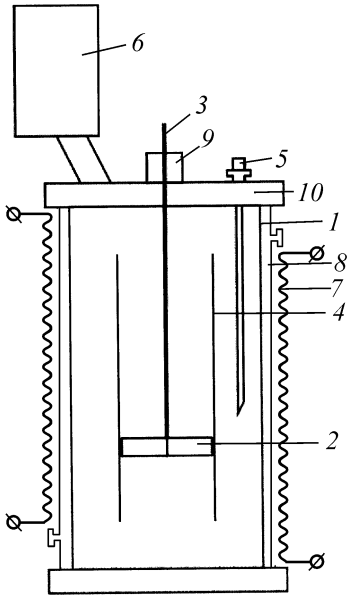

Fig. 1. The gas-liquid laboratory apparatus with the high speed agitator in the flow circuit. (*1–8*) see the test, (*9*) the end seal of the shaft, (*10*) the top inlet.

The agitator ensures the high value of the vertical component of the flow. The diameter and the slope of the blades are selected in accordance with the recommendations [3] in such a way that in the circulating container the flow would be directed upward along the axis of the apparatus, and in the radial clearance, downward. This direction of the motion of the liquid makes it possible to avoid an axial funnel in the upper part of the reactor.

The value of the gas saturation was determined as follows. After the switching on of the agitator and the gas feeding with the given flow the circulant liquid entrapped the fed gas, the gas saturation of the system occurred, the part of the gas saturated mixture from the apparatus was displaced into the expansion tank where changed the level ΔH of the gas–liquid mixture that was a governing parameter for determining the value φ.

Since the frequency of the agitator rotation n has the governing effect on the value of the gas saturation φ then the results of studies are processed in the form the functional dependence of the value of the gas saturation on the rotation frequency of the agitator at different parameters: the liquid viscosity, the flow of the gas reagents, the diameter of the agitator.

The characteristic dependence $\varphi = f(n)$ is pictured on Fig. 2. The water at temperature 18°C was used as the liquid medium, the nitrogen flow was 5.5 ± 0.1 cm^3 s^{-1}. The agitator diameter was 42 mm in all experiments.

We can distinguish three area on Fig. 2. The first area, from 1 to 16 Hz, is with weak growth of the gas suatiration caused by the low linear liquid velocity entrapping only small amount of the gas phase. The value of the gas saturation for the first area is less than 2%. In the second area a sharp increase in the gas saturation occurs. The third area starts from the frequency rotation about 30 Hz and conditioned by a sharp decrease in the speed of growth of the gas saturation value and by the output of a curve in the horizontal section. . In the third zone the gas saturation value reaches maximum for this system and it comprises 18%; with further increase in the number of revolutions of the agitators an insignificant increase in the gas saturation value occurs. The maximum value of the gas saturation for the apparatus similar to that investigated with the same characteristics of the process was 16% [3].

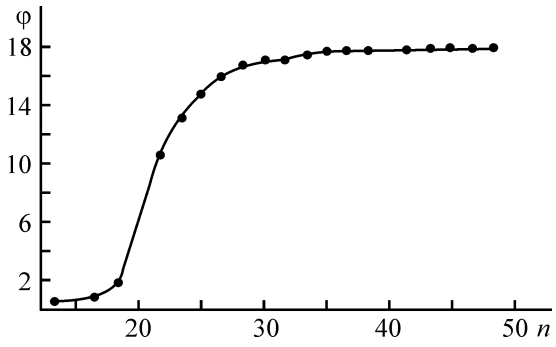

Fig. 2. Dependence of the gas saturation value φ (%) on the frequency of the agitator rotation *n* (Hz).

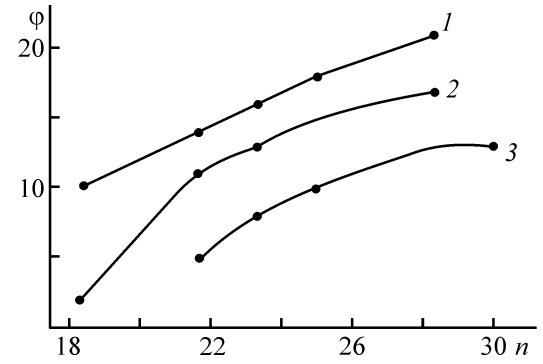

Fig. 3. Dependence of the gas saturation value φ (%) on the frequency of the agitator rotation *n* (Hz) for the medium of the various viscosities. Glycerol–water (volume): (*1*) 1 : 3, (*2*) 1 : 5, (*3*) water. Viscosity, cPoise (*1*) 14.8, (*2*) 5.2, (*3*) 1.0.

Figure 3 represents the graph of the dependence of the gas saturation value on the frequency of the rotation of the agitator. The viscosity of a liquid agent was changed, and the gas flow was about 5 cm^3 s^{-1}. We used the solutions of glycerol in the water of different volume concentration to get the liquids of the different viscosity.

The experimental results agree with the data published by Sokolov et al. [3] in accordance with which the gas content increases with an increase in the viscosity of the liquid medium. The *S*- shaped dependence of the gas saturation value on the frequency of the rotation of the agitator keeps with a change in the viscosity of the medium.

Upon an increase in the flow of the fed gas the maximum value of the gas saturation is attained at the smaller revolutions of the agitator (Fig. 4). The maximum value of the gas saturation practically does not depend on the flow of the fed gas.

We used two agitators with a diameter of 45 and 42 mm to determine the dependence of the gas saturation

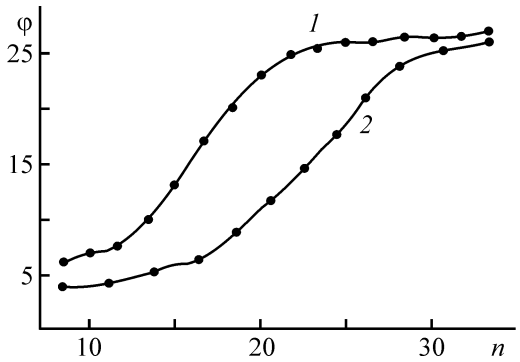

Fig. 4. Dependence of the gas saturation value φ (%) on the frequency of the agitator rotation *n* (Hz) at the various flows of the fed gas. The flow of the fed gas, cm^3 s^{-1}: (*1*) 28.0 ± 0.5, (*2*) 11.0 ± 0.3.

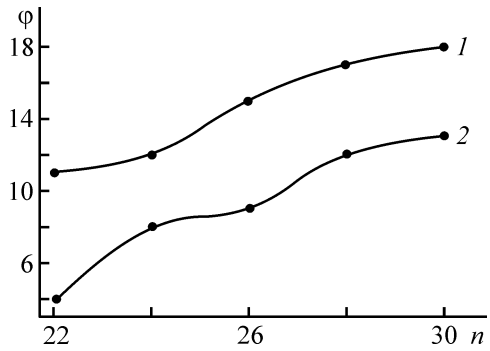

Fig. 5. Dependence of the gas saturation value φ (%) on the frequency of the agitator rotation *n* (Hz) at the agitator diameter (mm) (*1*) 45, (*2*) 42.

value on the frequency of the rotation of the agitator in the range of 22–30 Hz with different diameters of the apparatus. The experiment was carried out with constant flow rate of gas of 8.9 ± 0.2 $sm^3\ s^{-1}$

As it is shown on Fig. 5 the gas saturation value with the use of an agitator of larger diameter is higher than with one of smaller diameter. This agree with literature data, in accordance with which the gas saturation is proportional to the fifth power of the agitator diameter [4]. The ratio of the fifth powers of the diameters composes 1.41. A calculation by the experimental values shows that in the range of the frequencies of 25–29 Hz the ratio of the gas saturation values is in an interval of 1.41–1.47.

The value of the heat transfer coefficient from the reacting medium to the apparatus wall is important for the high exothermic gas–liquid processes. However, in the literature this information for the apparatus of the studied design was not found. Therefore on the laboratory setup (Fig. 1) experiences on the estimation of value α for this gas–liquid apparatus were carried out.

The experimental determination of the heat transfer coefficient from the flow of the gas–liquid mixture to the internal wall of apparatus was performed employing the following operation. We filled the jacket of apparatus with water and maintained near the boiling point with the aid of the electrical heater. Apparatus was filled with liquid at a temperature considerably greater than the boiling point of water. We measured the rate of the temperature decrease by the thermocouples installed in the gas–liquid medium with the agitator switched on, and under the gas feeding of the given flow. The inlets of apparatus were heat insulated. In the course of this experiment on the side of the apparatus the temperature was constant, and on the ends the heat flux that we neglected was constant.

The calculation of the heat transfer coefficient was conducted taking into account the weight of the inlets which had the same temperature as the gas–liquid mixture circulating in the apparatus.

Perfluorobutyl amine (bp 178°C) was selected as the liquid phase, and nitrogen fed at the flow 5 $cm^3\ s^{-1}$, as the gas phase. The frequency of the agitator rotation was 25 Hz. Under such conditions of the experiment value α was 470 $W\ m^{-1}\ K^{-1}$.

An error in the measurements of the geometric parameters, a length, a diameter, a thickness of the apparatus wall, and also of the medium temperature compose the summary error for computation of the heat transfer coefficient. Then $\delta = \Delta\alpha/\alpha = [(\delta H)^2 + (\delta D)^2 + (\delta l)^2 + (\delta T)^2]^{1/2}$, that is about 10%.

Results of the industrial apparatus test

Air flow, E, $m^3\ h^{-1}$	Height of the gas–liquid mixture in the separator, H, cm	φ, %
5	47	12
12.5	55	15
17.5	57	20

The experimental technique takes into account a thermal resistance of the apparatus wall, but the computation shows that at the wall thickness 3 mm the parameter $\lambda_{wall}/\delta = 3 \times 10^4\ W\ m^{-2}\ K^{-1}$ that is by two order of magnitude higher than the experimentally found heat transfer coefficient. Thus we neglected the temperature gradient over the apparatus wall.

An industrial gas–liquid apparatus with the high-speed agitator in the flow circuit with a volume 1000 l was designed on the basis of the obtained experimental data. The apparatus is equipped with jacket, high-speed agitator installed in the circulation pipe, with the temperature sensors, and the liquid motion. The inside diameter of reactor is 630 mm, the height of reactor, 3200 mm. The inside diameter of circulation pipe at entrance and outlet is 440 mm, on half of the length of pipe is located narrowing peace of 290 mm diameter and of 100 mm length. The length of an adapter from diameter 440 to the diameter 290 mm (and vice versa) is 130 mm. The circulation pipe is placed in the apparatus center at a distance 120 mm from the bottom and 150 mm from the cover.

In the center of the narrow peace of the circulation pipe there is an agitator of 260 mm diameter with a top coaxial drive. The end seal of TDM grade and of analogous type developed by Anod Ltd. (Nizhni Novgorod) is used for sealing the reactor along the shaft. Metal pairs of friction are applied to the end of the shaft, an electrical engine of power 25–30 kW, as a drive. The plate blade agitator was used in the apparatus. A number of the blades is 6, a slope to the rotation plane is 45°, a blade width, 60 mm. The frequency of the agitator rotation varies in the range of 25–50 Hz.

A technique analogous to one for the laboratory setup for measurement of the gas separation value was applied to an industrial apparatus test. The glycerol–water mixture with a volume ratio 1 : 3 was used as model liquid, air with various flow, as the gas phase. The medium temperature

was 18–20°C. The results of the experiment are listed in the table.

The number of revolutions of the agitator was constant and it was equal to 24 Hz. It follows from the data of the table that an increase in the flow of the fed gas leads to a growth of the gas saturation value that agrees with the experimental data obtained on the laboratory setup. The absolute value of gas saturation for the industrial apparatus exceeds the value of gas saturation for the laboratory setup by 2% and composes 20% with the same experiment conditions. It is conditioned by some changes in the construction of the industrial apparatus (decrease in the ratio of the agitator diameter to the inside diameter of the circulation pipe) and by more precise determination of the volume of the gas–liquid mixture in the separator.

CONCLUSIONS

(1) The characteristic dependence of the gas content of the liquid on the frequency of the agitator rotation was obtaned. It was demonstrated that it is S-shaped dependence with three areas. The maximum value of the gas saturation attains 25%. A sharp increase in the gas content occurs upon changing the frequency of the rotation form 18 to 27 Hz.

(2) The maximum value of the gas saturation grows from 13 to 18% at an increase in the agitator diameter by 3 mm.

(3) Changes in the medium viscosity at various frequencies of the agitator rotation from 1 to 14 cPoise lead to the growth of the gas saturation from 14 to 21%.

(4) The heat transfer coefficient α from the liquid flow to the inside wall of the reactor was determined (470 W m^{-2} K^{-1}.

(5) Results of the laboratory study of the gas saturation were confirmed under industrial conditions for an apparatus of volume 1 m^3.

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