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Vortex centrifugal bubbling reactor

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Abstract

The vortex centrifugal bubbling apparatus is considered as a basis for a new type of multiphase vortex centrifugal bubbling reactor. In this device, a highly dispersed gas–liquid mixture is produced in the field of centrifugal forces inside the vortex chamber. The operation of the vortex centrifugal bubbling apparatus is based on the rotation of liquid by the tangential entry of gas flows via the many tangential guiding vanes around the periphery of the vortex chamber. At certain regimes there appears a highly dispersed gas–liquid vortex bubbling layer. Vortex bubbling layer represents the following unique characteristics: low hydrodynamic resistance (1000–2000 Pa); homogeneity and stability over wide range of centrifugal acceleration (10^2 to 10^3 m/s^2); large specific surface with the high renovation rate (of about 5 m^2 per 1 l of water); high gas content (of about 0.5–0.6); high gas throughput (up to 200–300 m^3 of gas per 1 l of liquid per hour) and, consequently, very high rates of heat and mass transfer. The energy consumption for the vortex bubbling layer maintenance is about 50–80 W per 1 l of treated liquid. The design features of the vortex chamber are described in view of the methods of stabilization of the vortex bubbling layer. The data on the hydrodynamic resistance, the structure and the lifetime of the vortex gas–liquid layer are presented. The main advantages and features of the devices of this type are discussed in view of their possible application.

Keywords: Vortex centrifugal bubbling apparatus; Gas–liquid reactors; Multiphase reactors

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1. Introduction

One of the topical tasks in modern chemical technology is efficient carrying out chemical processes in the multiphase media. Currently, various types of multiphase gas–liquid reactors are used for accomplishing the gas–liquid multiphase reactions [1]. The main destination of these devices is an increase of the rate of mass-exchange between gases and liquids by increasing the interfacial area and its turbulization in order to enlarge the mass transfer rate constant. For these purposes, various types of bubble and packed-bed column apparatuses are the most widely used.

However, such devices have a number of shortcomings. Typically, they represent high hydrodynamic resistance, weak mixing of liquids that does not allow carrying out the efficient processing of immiscible liquids, low gas throughput, the complexity of the performance of reactions with the large heat effects, the occurrence of pulsations and vibration as well as a constructive complexity. Special complicated packed-beds are necessary for efficient work of the packed-bed column reactors. Another disadvantage is the large size of such devices due to the small value of the gas–liquid interfacial area per unit of the reactor's volume. As a rule, such reactors are characterized by long time of residence of both reagents and products in the reaction zones.

The solution of contemporary problems of chemical engineering needs often to fulfil a wide complex of requirements that exceed the capabilities of the above mentioned devices: short times of the contact of reacting phases; coupling of the mixing and division processes; small dimensions of the reactor at its large productivity as well as high rates of the mass and heat transfer, low hydrodynamic resistance of the reactor. Thus, the development of principally new approaches to the multiphase reactors design that allow overcoming the disadvantages mentioned above would be highly appreciated. A vortex bubbling device which is proposed in this paper makes

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Nomenclature

Nomenclature

a	centrifugal acceleration in the units of g
d	characteristic particle size
F	force
G	gas mass flow rate
g	gravity acceleration
h	height of vortex chamber at the radius r
Q	gas volume flow rate
r	radial coordinate, radius of vortex chamber
S	particle cross-section surface
v	velocity

Greek letters

σ	surface tension coefficient
ω	angular velocity
ζ	drag coefficient
ρ	density

Subscripts

l	liquid
g	gas
r	radial velocity component
φ	azimuth velocity component
c	centrifugal force
pr	pressure force
res	media resistance force

a promising basis for solving at least some of the mentioned problems.

2. Principle of operation of vortex centrifugal bubbling apparatus

Currently, various kinds of the vortex centrifugal devices are known [2]. In the vortex centrifugal bubbling device a highly dispersed gas–liquid mixture is produced and held in the field of centrifugal forces inside the vortex chamber. The operation of the vortex centrifugal bubbling device is based on the rotation of liquid by the gas flows (Fig. 1) coming through many tangential slits between the guiding vanes around the periphery of the vortex chamber (Fig. 2). At certain operating parameters there appears a highly dispersed gas–liquid vortex bubbling layer (Fig. 3). The gas passes through the vortex bubbling layer and leaves the vortex chamber through a central orifice in one or both end walls. The transport of the liquid may be organized for its subsequent utilization. The vortex centrifugal bubbling apparatuses have small overall dimensions at high efficiency.

Various designs of the vortex centrifugal bubbling apparatuses have been described [5–7]. Some operating regimes with the certain gas and liquid feed rates that provide the formation of the dispersed vortex gas–liquid layer at the periphery of the vortex chamber are considered in [4].

The vortex centrifugal bubbling apparatuses have already been applied to the several technical tasks, such as gas streams cleaning from dust, damping of air and some others [8,9]. There is an example of the use of such type apparatus to enhance the oxidative cleaning of water solutions from the hydrogen sulfide [3]; the published data show that the reactor based on the vortex centrifugal bubbling apparatus allows achieving the productivity larger than in an ordinary bubbling column reactor at the comparable energy consumption in some ten times. Unfortunately, despite such kinds of apparatuses represent the doubtless advantages, they are practically unknown in chemical industry due to certain adaptation problems.

3. Merits and demerits of existing vortex centrifugal bubbling devices

The unique merits of the vortex centrifugal bubbling apparatuses are the following:

- Low hydrodynamic resistance of about 100–200 mm of H_2O in contrast to that of the conventional bubble and packed-bed columns based on gravitational bubbling where the hydrodynamic resistance is 10 or 100 times lager;

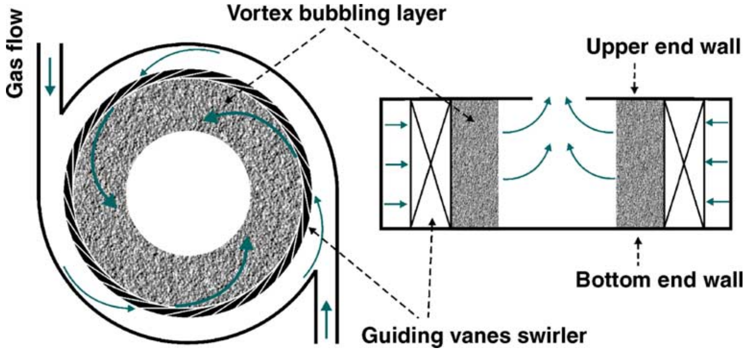

Fig. 1. Principle of operation of the vortex centrifugal bubbling apparatus.

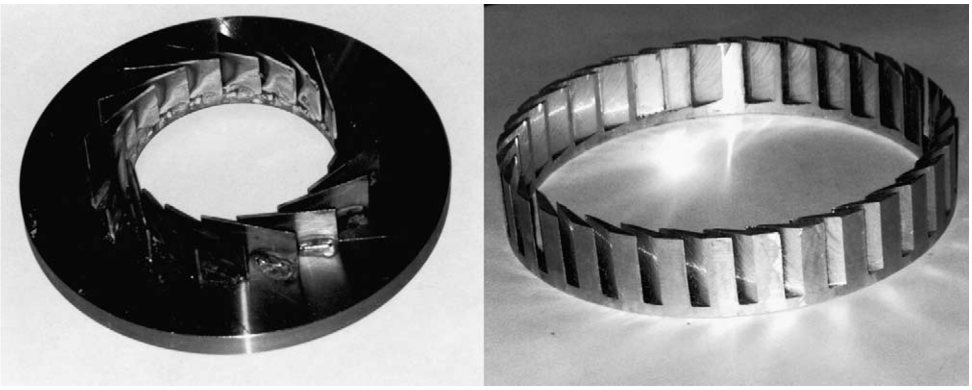

Fig. 2. Two types of the guiding vanes swirlers.

- The gas–liquid interaction takes place in the field of centrifugal forces at centrifugal acceleration in the range of 10^2 to 10^3 m/s^2 (against the acceleration of gravity 9.8 m/s^2) that provides the large specific surface of about 5 m^2 per 1 l for water–gas interface with the very high surface renovation rate, high gas content of about 0.5–0.6 and homogeneity of vortex bubbling layer;
- The size of the vortex centrifugal bubbling apparatuses is up to 10 times smaller in comparison with conventional bubbling equipment at the similar productivity due to the high ratio of specific surface value to the volume of vortex chamber which makes approximately 10^3 m^2/(m^3 of vortex chamber);
- High gas throughput: up to several thousands of gas volumes may pass through one volume of the liquid per minute that provides a large heat transfer efficiency and the short time of the gas–liquid contact up to 10^{-2} s;
- As a result, the very high rates of heat and mass transfer can be achieved in such type of devices.

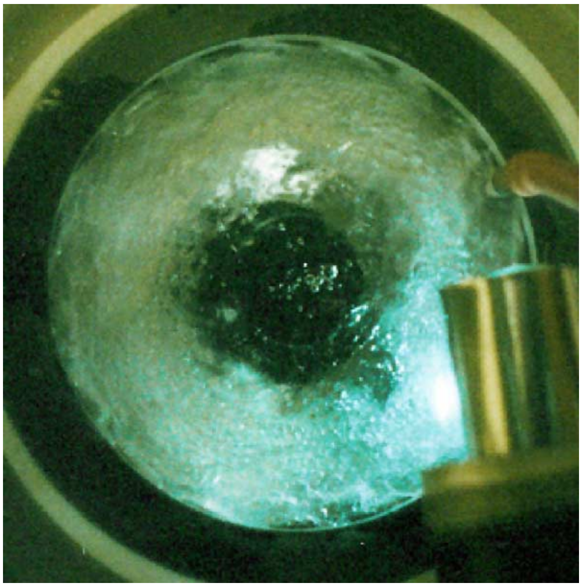

Fig. 3. A general view of the vortex centrifugal bubbling layer.

Though these devices enable to overcome many of the abovementioned shortcomings, which are typical for the well known bubble and packed-bed columns, they have their own disadvantages, limiting their further development and application in chemical industry.

Thus, an essential peculiar disadvantage of the known vortex centrifugal bubbling apparatuses is the appearance of a sufficient instability of the vortex bubbling layer leading to the uncontrolled liquid carrying away from the vortex bubbling layer by the gas flow leaving the vortex chamber. This results in a narrow working range of operating parameters of the vortex chamber as well as in the impossibility of the liquid processing without its recirculation. This restricts significantly the possibility to control many essential operating parameters of the vortex chamber such as the ratio of gas and liquid flow rates, hydrodynamic resistance, gas content and centrifugal acceleration, which determine the structure and dispersity of the vortex gas–liquid layer. From the other hand, there is a lack of a theoretical basis for the computation of the operating parameters for such devices as well as the absence of reliable experimental data on the structure and properties of the vortex gas–liquid layers.

In this paper the origins of the vortex bubbling layer instability are examined and the methods for its suppression are discussed. Some new results are obtained on the structure and properties of the vortex gas–liquid layer and the operating parameters of the vortex centrifugal bubbling apparatus. The main peculiarities of the vortex centrifugal bubbling devices are listed in order to make clear their potential applications in chemical technology.

4. Origin of the vortex bubbling layer instability and methods of its stabilization

Let us examine some of the causes of the vortex gas–liquid layer instability, in particular the phenomena of the uncontrolled liquid carrying away from the vortex bubbling layer by the gas flow leaving the vortex chamber, and possible ways of its elimination (Fig. 4) [10].

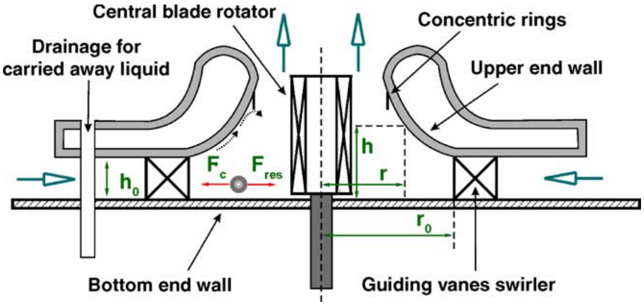

Fig. 4. Design of the vortex chamber with controlled liquid entrainment.

Firstly: the carrying away of a liquid occurs in the form of a liquid film moving along the end walls towards the axis region due to entrainment of the liquid near the end walls by gas flow. This so-called “end wall effect” or “end wall entrainment” is due to the lack of cyclostrophic balance that is considered as the parity between the radial pressure gradient and the centrifugal force. Indeed, near the end wall surfaces the azimuthal velocity and consequently the centrifugal acceleration sharply decrease due to the boundary layer effect induced by the frictional force. From the other hand the radial pressure gradient essentially remains the same as in the core region. These results in the moving of the liquid film formed on the end wall surface along from the periphery of the vortex chamber to the central exit orifice, as shown in (Fig. 4) by the dashed lines with arrows.

It is possible to decrease the “end wall entrainment” of the liquid by the separation of the liquid film from the end wall surface somewhere near the axis region with the subsequent return of the liquid back to the vortex gas–liquid layer. This task may be resolved by placing of the concentric rings at one or both end wall surfaces near the inner boundary of the vortex gas–liquid layer (Fig. 4).

Secondly: the carrying away of the liquid also occurs in the form of droplets entrained by the gas flow through the near axis region of vortex chamber. The liquid droplets of various sizes are formed at the inner boundary of the vortex bubbling layer. The largest droplets are separated by the centrifugal force and returned back to the vortex gas–liquid layer, while the smaller droplets are entrained by the gas flow. The origin of this effect is the low gas circulation in the near axis region due to angular momentum loss in the vortex gas–liquid layer. This situation may be partly improved by bringing an additional swirl in the near axis region of the vortex chamber by applying of the central blade rotator (Fig. 4).

Thirdly, to provide a stable operation of the vortex centrifugal bubbling apparatuses it is necessary to ensure the maintenance of the cyclostrophic balance in the whole working volume within the vortex chamber where the vortex bubbling layer is sustained. It can be ensured mainly by appropriately profiling the end walls of the vortex chamber. Otherwise, the segments of the vortex bubbling layer will not be located on the set of equilibrium circular orbits and, in particular, will move along the chords with subsequent carrying away from the vortex chamber (Fig. 5).

Fig. 5. An example of the unstable vortex centrifugal bubbling layer.

In order to maintain the cyclostrophic balance along the wide range of radiuses, the vortex chamber should have a certain end wall profile. The cyclostrophic balance keeps in the case when the resultant of forces affecting the droplet within the vortex gas–liquid layer is equal to zero. These forces are the centrifugal force F_{c}, the pressure gradient force F_{pr} and the force of hydrodynamics resistance F_{res} (Fig. 4).

$$F_{\mathrm{c}} = \rho_{\mathrm{l}} S d \frac{v_{\varphi}^2}{r}, \quad F_{\mathrm{pr}} = \Delta p S = \rho_{\mathrm{g}} S d \frac{v_{\varphi}^2}{r}, \quad F_{\mathrm{res}} = \zeta \rho_{\mathrm{g}} S \frac{v_r^2}{2} \tag{1}$$

Here d is the typical particle size, S the mean cross-section area of particle, ρ_{l} the liquid density, ρ_{g} the density of gas, v_{φ} the azimuth velocity, v_r the radial velocity and ζ the drag coefficient. We assume the particle tangential velocity to be the same as the gas flow one.

It was assumed that the gas flows around the particle in radial direction at high Reynolds number, so that the quadratic drag low is valid.

At calculating the pressure gradient force it had been assumed that it is mainly provided by the centrifugal force, the droplets being small enough to neglect the change of centrifugal acceleration along their length. Taking into account the fact that $\rho_{\mathrm{l}} \gg \rho_{\mathrm{g}}$, the neglect of the pressure gradient force in comparison with the centrifugal force is making possible.

Thus, the cyclostrophic balance for the droplets in the vortex chamber can be written as follows:

$$F_{\mathrm{c}} = F_{\mathrm{res}} \tag{2}$$

The gas mass flow conservation equation will give:

$$G = 2\pi r h(r) \rho_{\mathrm{g}} v_r = \mathrm{const} \tag{3}$$

From formulas (1), (2) and (3) we can get the relation between $h(r)$, determining the end -wall profile (Fig. 4), and $v_\varphi(r)$ as follows:

$$h^2(r)v_\varphi^2(r)r = \frac{\zeta G^2}{8\pi^2\rho_l\rho_g d} \tag{4}$$

Here the right hand side does not depend on r. So, the profile law is:

$$h(r) = h_0\frac{v_\varphi(r_0)}{v_\varphi(r)}\left(\frac{r}{r_0}\right)^{-1/2} \tag{5}$$

where h_0 the height of the vortex chamber at the inner radius r_0 (Fig. 4).

The circular motion in the vortex gas–liquid layer is close to quasi-solid rotation:

$$v_\varphi = \omega r \tag{6}$$

Thus, we can find from (5) and (6)

$$h(r) = h_0\left(\frac{r_0}{r}\right)^{3/2} \tag{7}$$

Formula (5) is the generalization of the end wall profile law for the flow regimes, which do not follow the linear radius dependence of the azimuth velocity. The experiments have showed that the ≪3/2≫ law for the upper end wall profile in comparison with the plane one significantly improves the stability characteristics of the vortex gas–liquid layer, enlarging its volume and sharply enhancing the working range of operating parameters of the vortex chamber.

If the power in the end wall profile law is larger then 3/2, the centrifugal force dominates. In this case the vortex gas–liquid layer will be pressed to the guiding vanes and thus destabilized too.

5. Experimental

The hydrodynamic experiments were performed with a "cold" model of the vortex reactor (Fig. 6) with a closed air circuit, including successively a ventilator, which provided the air circulation through a straight tube with a gas flow rate measuring device, the guiding vanes swirler, the vortex chamber and a buffer volume between the chamber and the ventilator inlet. By changing the rotation frequency of the ventilator we were able to provide the airflow rate up to 100 m^3/h.

The vortex chamber contained a guiding vanes swirler of 100 mm diameter, a plane bottom end wall and an upper end wall with a central orifice. The upper end wall could be either plane or profiled. We used in our experiments: (i) the vortex chamber with the plane upper end wall with the orifice of 30 mm diameter (150 ml volume); (ii) the vortex chamber with the upper end wall profiled according to "3/2" law with the orifice of 52 mm diameter (280 ml volume); (iii) the vortex chamber with the upper end wall profiled according to "3/2" law with the orifice of 52 mm diameter, furnished with concentric rings of the width of 1 mm, the height of 4 mm and of the diameters of 75 and 80 mm (280 ml volume). The guiding vanes swirler of the blade type was of 18 mm height and had 18 tangential slits of 1.8 mm width. Besides, there was a possibility to arrange a blade rotator of 40 mm diameter in the center of the vortex chamber with an independent motor.

In order to create a vortex bubbling layer, the liquid was introduced into the vortex chamber by measured portions through the orifice in the bottom of the vortex chamber.

The appearance, existence and disappearance of the vortex bubbling layer were registered visually through the transparent side windows of the reactor and the transparent bottom end wall of the vortex chamber. The time of the disappearance

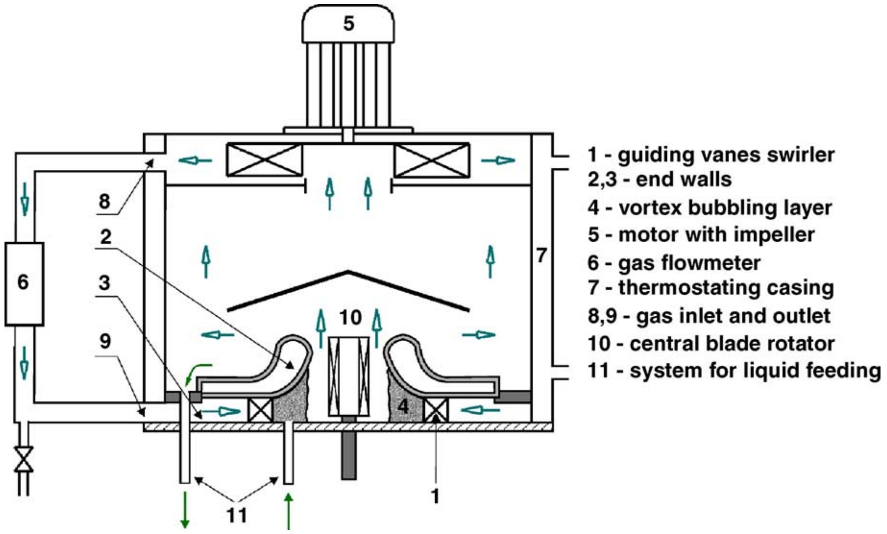

Fig. 6. Scheme of an experimental model of the vortex centrifugal bubbling reactor.

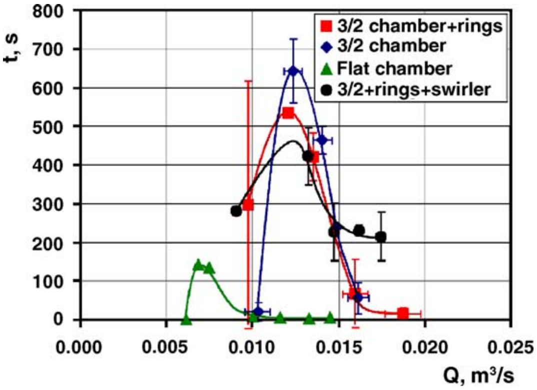

Fig. 7. Lifetime of a vortex bubbling layer as a function of the gas flow rate at the different designs of the vortex chamber.

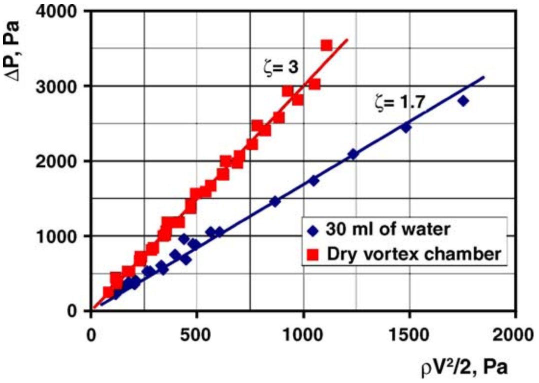

Fig. 8. Typical behavior of the hydrodynamic resistance of the vortex chamber as a function of the gas flow rate.

of the vortex bubbling layer was registered at the moment when the blades of the guiding vanes swirler become visible.

The measuring device for the airflow rate was a standard restriction with temperature and pressure probes in a straight tube of 30 mm diameter. The pressure drop was measured by electronic pressure cell Testo-505-P1. The temperature was measured by standard thermocouples. In order to register the rpm of the central blade rotator, the distance tachometer Testo-465 was used.

6. The stability and hydrodynamic regime characteristics of vortex bubbling layer

Several series of experiments had been made to demonstrate the influence of geometric and operating parameters of the vortex chamber on the stability of the vortex gas–liquid layer as discussed earlier. The experimental results are represented on Figs. 7 and 8.

In (Fig. 7) the experiments are shown on the maintenance of the vortex bubbling layer, which was created by insertion into the vortex chamber of a portion of water (40 ml in our

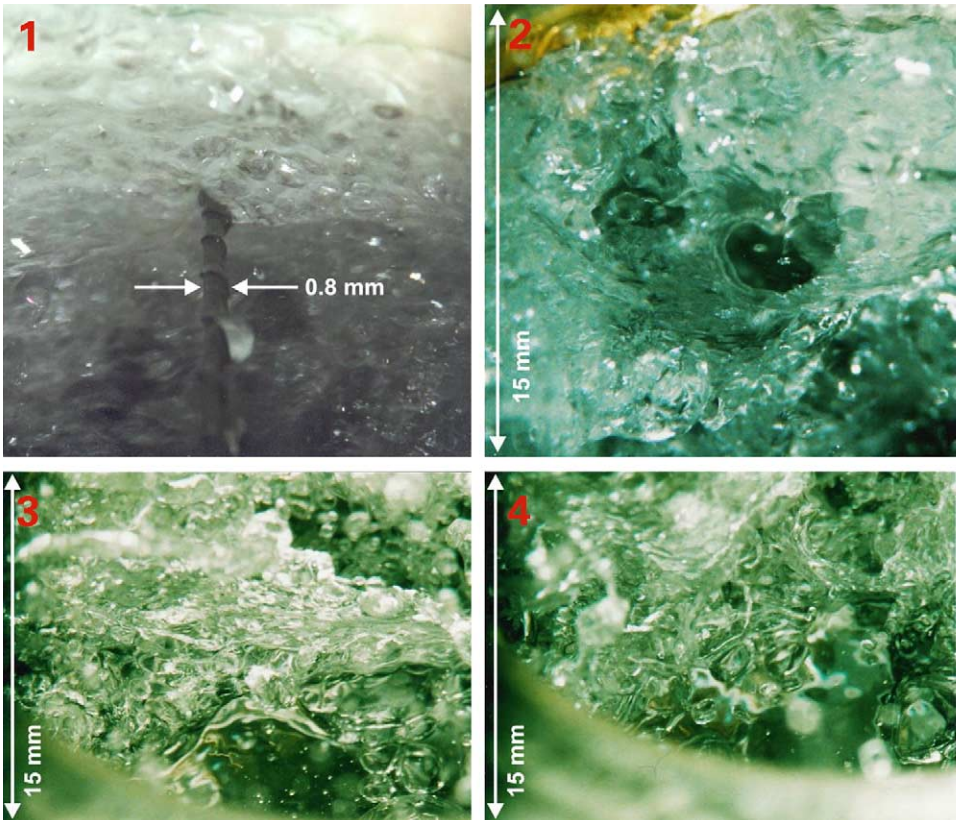

Fig. 9. Photos of the structure of the vortex centrifugal bubbling layer. Time resolution–10^{-4} s. (1) low gas flow rates, (2–4) high gas flow rates.

Table 1
Basic properties of the vortex centrifugal bubbling device

Properties of vortex bubbling layer	Homogeneity and stability at centrifugal acceleration in the range of 10–100 g. Large specific surface of about 5–10 m^2/l of liquid or above 10^3 m^2/m^3 of vortex chamber with very high renovation rate. High gas content of about 0.5–0.6.
Low hydrodynamic resistance	The vortex chamber with a vortex bubbling layer has the low hydrodynamic resistance of about 100–200 mmH_2O that enables to serve it by a common ventilator and provides relatively low specific power to support it.
High gas throughput	The vortex centrifugal bubbling apparatuses provide high gas throughput: several thousands of gas volumes can pass through one liquid volume per minute, ensuring high rates of heat transfer and the short time of gas–liquid contact down to 10^{-2} s.
Dispersions of immiscible liquids	In the vortex bubbling layer with immiscible liquids, a high disperse emulsion is created and thus the high contact surface arises that enables carrying out numerous chemical processes without phase transfer agents.
The possibility of coupling of mixing and division processes	In the apparatus of the proposed type the high rates are achieved for both: the gas components transport to the liquid and extraction of volatile substance from the liquid into the gas. This suggests considering the vortex centrifugal bubbling apparatuses as an alternative to membrane reactors for solving the some specific problems of chemical technology.
Scalability	The proposed technology is well scalable. The vortex chamber may be designed to treat up to 2 m^3 of liquid. It is also possible to design a reactor with a series of vortex chambers served by a single gas pump.
Size and maintenance	The vortex centrifugal bubbling apparatus has simple design and small overall dimensions at high efficiency. The vortex centrifugal bubbling apparatus is up to 10 times smaller than conventional bubbling equipment at similar productivity due to the high ratio of the specific surface value to the volume of the vortex chamber which constitutes approximately 10^3 $m^2/(m^3$ of vortex chamber volume). There is no need to use any packed bed of a complicated shape for the enlargement of the interfacial area.

Consequently, the unique characteristics of vortex bubbling layer look very promising for further application in chemical technology, in particular for the creation of fundamentally new highly efficient vortex gas–liquid reactors.

case) without any additional liquid feeding. The lifetime (s) of this vortex gas–liquid layer is shown as a function of gas flow rate (m^3/s) at different geometry of the end walls and with or without the center blade rotator. Each experiment was repeated for the several times and the corresponding error bars are represented on plots (sometimes they are located within the experimental marks).

It is clear that the lifetime of the vortex gas–liquid layer is mostly influenced by profiling of the end walls of the vortex chamber and a correct choice of the gas flow regime (Fig. 7). The vortex chamber with the plane end walls represents the narrowest working range of operating parameters at which the vortex bubbling layer exists. Profiling of the upper end wall according to the “3/2” law considerably increases both the lifetime and working range of the operating parameters of the vortex chamber. Furnishing of the end walls with the concentric rings makes some additional impact on the stability only at the large gas flow rates. It can be used if high intensive vortex gas–liquid layers are necessary. The use of a central blade rotator together with concentric rings is also worthwhile at the large gas flow rates. The left part of the “lifetime curve” with the largest error bar demonstrates a typical threshold behavior, as at too low gas flow rate the centrifugal force cannot surmount the gravity so that all the liquid or some part of it remains rotating at the bottom end wall.

The plots in (Fig. 8) show the pressure drop (Pa) as a function of the flow strength ($\rho_g v_s^2/2$, where v_s is the gas velocity in the slits between the guiding vanes). The first line represents the case of the “dry” vortex chamber and the second line the case when the vortex gas–liquid layer was created as described before. These experiments were made with the optimized upper end wall, profiled according to “3/2” law and furnished with the concentric rings. The slopes of the lines characterize the hydrodynamic resistance of the apparatus.

Fig. 8 shows that the appearance of the vortex gas–liquid layer in the vortex chamber sharply reduces its hydrodynamic resistance.

7. Structure of the vortex bubbling layer

Experimental data regarding the vortex bubbling layer structure are obtained with the help of macro-photography at ultra short exposures below than 10^{-4} s. Some photographs are presented at (Fig. 9). It is clearly recognized that the vortex bubbling layer has a bubbling-foam structure with the typical thickness of the liquid films of about 0.1 mm, if the gas flow rate is not too high. As the gas flow rate increases the extremely intensive mixing in the vortex bubbling layer is observed. This demonstrates its peculiar properties: the characteristic scales of the velocity and size perturbations on the interfacial boundary and consequently the sizes of droplets and bubbles, arising at ruptures of the interphase surface, lay in a wide range down to the very small scales, less that it is suggested by the Laplace formula, that evaluates the scale from the balance of gravitational (centrifugal) and surface tension forces:

$$d = \sqrt{\frac{\sigma}{ag(\rho_l - \rho_g)}} \tag{8}$$

Here σ is the surface tension coefficient, g the gravity acceleration, a the centrifugal acceleration in the units of g.

Hence, the vortex bubbling layer represents a medium in which the highest rates of the heat and mass transfer can be achieved per unit of the reactor volume.

8. Dispersion of immiscible liquids

One of the essential features of the vortex bubbling layer is the possibility of efficient carrying out various chemical processes in systems with immiscible liquids. In this case, even without any additions of surfactants in the vortex layer, a high disperse emulsion (water–gasoline system is an example) can be obtained, having the typical opalescence coloring and stability for several weeks.

This circumstance enables getting a high contact surface between the immiscible liquids and thus carrying out of numerous chemical processes without using the phase transfer agents.

9. Conclusions

The above discussion evidences that the vortex centrifugal bubbling apparatus can be considered as a basis for a new promising type chemical reactors. The methods were suggested to enhance the efficiency of such devices and their applicability in the chemical technology by an essential increasing of the stability and lifetime of the vortex bubbling layer and of the working range of operating parameters at which the vortex bubbling layer exists. The experimental data on the lifetime of the vortex bubbling layer and some operating parameters in the model vortex chamber are presented. Some preliminary data on the structure of the vortex bubbling layer and on the possibility of carrying out processes with immiscible liquids are obtained.

Thus, taking into account the very interesting possibilities of the chemical reactors on the basis of the suggested approach their further development and additional investigation are needed. So, a further studies are necessary of the mass transfer efficiency in the vortex bubbling layer and of its connection with such physical parameters of the vortex bubbling layer as the interfacial area, its renovation rate and with geometrical and operating characteristics of the vortex chamber. A detailed research is needed of operating parameters of vortex chamber and their influence on the vortex bubbling layer stability. Also, finding the adequate theoretical models are needed to describe hydrodynamic and chemical processes in such devices.

Table 1 summarizes the key features of the devises of the suggested class.

Acknowledgments

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