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HYDRODYNAMIC AND ENERGY PARAMETERS OF GAS-LIQUID MEDIA

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Abstract. The paper presents the results of studies related to determining the interconnections between hydrodynamic and energy parameters of gas-liquid media. The whole scope of information about them taken together allows evaluating the prospects of searching for new technologies and their improvement. In the studies, phenomenological generalizations of theories that comply with Archimedes', Henry's, Pascal's laws and the superposition principle have been used to determine the driving and resistance factors when circulation circuits of media appear.

It is shown that the energy potential of the latter results from the dissolution of the gas phase and the synthesis of the dispersed gas phase during self-organized or forced processes. These two causes are interrelated, but their manifestations are different. The presence of a dispersed gas phase, regardless of the form it appears in, a priori means the presence of a driving factor in the creation of circulation circuits, whereas the presence of a dissolved gas phase is only the root cause of the formation of the dispersed gas phase. In anaerobic processes, gas phase is represented by carbon dioxide, and in aerobic, by air or nitrogen from the composition of air and CO_2. The total driving potential of circulation circuits is determined by the gas-holding capacity that, in turn, depends on the intensity of the synthesis of the dispersed gas phase, on the geometry of the media volumes, and on the physical properties of the phases. The gradient by the level of saturation of the liquid phase by the gas phase is determined basing on their physical and chemical properties and by the hydrostatic pressures of the liquid phase. The boundary saturation depends on the gas phase pressure in the supraliquid volume and the hydrostatic pressure. It is shown that a factor that intensifies mass-exchange processes is the relative rate of emergence of the bubbles in the gas phase. Calculation formulae are developed to estimate the gas-holding capacity and driving factors in the form of Archimedes' buoyant forces. It is pointed out how important circulation circuits are in creating desaturation and saturation zones of media in order to improve the living conditions for microorganisms.

Key words: gas-holding capacity, saturation, pulse, solubility, gas phase, mass exchange.

ГІДРОДИНАМІЧНІ ТА ЕНЕРГЕТИЧНІ ПАРАМЕТРИ ГАЗОРІДИННИХ СЕРЕДОВИЩ

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Анотація. У статті наведено результати досліджень, пов'язаних із визначенням взаємозв'язків між гідродинамічними і енергетичними параметрами газорідинних середовищ. Поєднання інформації щодо їхньої сукупності дозволяє оцінювати перспективи пошуків у напрямках удосконалення і створення нових технологій. У дослідженнях використовували феноменологічні узагальнення теоретичних положень, що відповідають законам Архімеда, Генрі, Паскаля і принципу суперпозиції для визначення рушійних факторів і факторів опору при виникненні циркуляційних контурів середовищ.

Показано, що енергетичний потенціал останніх створюється на основі явища розчинення газової фази та синтезу диспергованої газової фази в умовах самопливних або примусових процесів. Ці дві причини взаємопов'язані, однак прояви їхні різні. Присутність диспергованої газової фази незалежно від форми її виникнення вже означає наявність рушійного фактора у створенні циркуляційних контурів, тоді як присутність розчиненої газової фази є лише першопричиною утворення диспергованої газової фази. В анаеробних процесах газова фаза представлена діоксидом вуглецю, а в аеробних – повітрям або азотом зі складу повітря і CO_2. Сумарний рушійний потенціал циркуляційних контурів визначається показником газоутримувальної здатності, який залежить від інтенсивності синтезу диспергованої газової фази, геометрії об'ємів середовищ та фізичних властивостей фаз. Градієнт по рівню насичення рідинної фази газовою визначається фізико-хімічними властивостями останніх і гідростатичними тисками рідинної фази, а граничне насичення залежить від тиску газової фази в надрідинному об'ємі та гідростатичного тиску. Показано, що фактором інтенсифікації масообмінних процесів є відносна швидкість спливання бульбашок газової фази. Одержано розрахункові формули для оцінок газоутримувальної здатності і рушійних факторів у формі

Архімедових сил. Вказано на важливу роль циркуляційних контурів у створенні зон десатурації та сатурації середовищ з метою поліпшення умов життєдіяльності мікроорганізмів.

Ключові слова: газоутримувальна здатність, насичення, імпульс, розчинність, газова фаза, масообмін.

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Introduction. Formulation of the problem

A lot of technologies of food, microbiological, and pharmaceutical industries are involved in gas-liquid media where gas phases are formed forcedly or result from self-organized chemical or biochemical processes. These two directions are represented by the processes of anaerobic and aerobic fermentation of sugar-containing media with intensive energy and mass exchange and synthesis of target substances. The energy resource of fermentation processes in these technologies is represented by nutrient components in the form of organic, mineral substances, biostimulants, etc. at the level of chemical energy. At the same time, the energy potential of the media increases significantly with the creation of a dispersed gas phase in them.

The integration of information about hydrodynamic and energy parameters of gas-liquid media should be viewed as a promising research direction to create new effective equipment for technological processes.

Analysis of recent research and publications

The development of modern principles of the hydrodynamics of gas-liquid or liquid systems with solid-state elements focuses on computer modeling aimed at finding means of intensifying mass-exchange processes [1,2], and increasing the interphase surface in relation with constructive features and geometric proportions [3,4]. Principal approaches are found in the estimations of anaerobic and aerobic processes [5] on the basis of mathematical formalizations [6,7]. Of interest are the approaches concerning the active phase of interactions in gas-liquid media, which relate to the forced creation of transition processes [8,9]. The presence of a dispersed gas phase in the liquid phase allows considering such a system to be a quasiresilient one [10-12]. It opens new opportunities in the organization of innovative technologies. Hydrodynamic modes in the conditions of aerobic and anaerobic fermentation processes are associated with the existence and creation of energy potentials [13], and are correlated with other fields of investigation of gas-liquid media [14-18].

The purpose of the paper is to evaluate the interconnections between the hydrodynamic and energy parameters of gas-liquid media and to find methods of intensifying the technological processes of fermentation.

Tasks of the research.

1. To confirm the presence of energy potentials in gas-liquid media in the form of such carriers as dissolved gases and dispersed gas phase.
2. To determine the driving forces of circulation circuits in gas-liquid media.
3. To determine the factors that effect on the gradient of saturation of the liquid phase with dissolved gas and on the boundary saturation.
4. To develop mathematical formalizations concerning the rate of emersion of the dispersed gas phase, gas-holding capacity, and driving factors.

Research materials and methods

In analytical phenomenological studies, the theoretical principles and findings were used on the hydrodynamics of gas-liquid media, the determination of driving and resistance factors related to the dynamics of circulation circuits and the possibilities of intensifying technological processes.

Results of the research and their discussion

In alcohol, brewing, and wine-making industries, in anaerobic processes involving yeast of saccharomycetes, the incoming streams of sugars are transformed into alcohol and carbon dioxide in proportions complying with Gay-Lussac’s law and the laws of conservation of mass and energy [8, 11]. The boundary parameters of fermentation processes are limited by microorganisms. These parameters include the temperature of the medium, the concentration of nutrients and products of their decomposition, pH values, and so on. This complex is important both in correlations and in their generalizations at the levels of osmotic pressures. All other conditions being equal, the hydrodynamic state of the gas-liquid medium plays a principal role. Its main indicator is the one-moment volume of the dispersed gas phase contained in it. This volume determines the energy characteristics of the circulation circuits, the level of swelling of the medium and its potential energy, the intensity of mass exchange processes. The combination of gravitational field effects, hydrostatic pressure, and manifestations of Henry’s and Archimedes’ solubility laws leads to the formation of a hydrodynamic energy potential of a medium created in self-organized processes of carbon dioxide synthesis followed by the processes of saturation of the liquid phase and the formation of a dispersed gas phase [12, 13].

Endogenous synthesis of CO_2, as well as the saturation of the liquid phase, does not change the physical properties of the medium.

From the beginning of the formation of the gas phase in the form of CO_2 bubbles, the total volume of which determines the gas-holding capacity of the medium, Archimedes' law effects itself in the form of the emergence of the circulation circuits of the gas-liquid mixture.

The bubbles formation of the gas phase requires energy costs E_b for the synthesis of the phase separation surface in accordance with the dependence:

$$E_b = \sigma f \text{ , J,} \tag{1}$$

where σ is the coefficient of surface tension, J/m^2;
f is the phase separation surface area.

The equality of the Archimedean forces and the forces of the resistance of the medium corresponds to the stabilized relative velocity w_{rel} of the emersion of gas bubbles with diameter d_b :

$$P_{Ar.} = \rho g V; \quad P_{r.f.} = \xi f_0 \frac{w_{rel}^2}{2}; \tag{2}$$

$$\rho g V = \xi f_0 \frac{w_{rel}^2}{2} , \tag{3}$$

where ρ is the specific mass of the liquid phase, kg/m^3;
g is the acceleration of free fall, m/s^2;
V is the volume of a gas bubble, m^3;
f_0 is the area of the cross-section of a bubble, m^2;
ξ is the coefficient of resistance of the medium, kg/m^3.

From conditions (2) and (3) follows:

$$w_{rel} = \sqrt{\frac{32 \rho g d_b}{3\xi}} . \tag{4}$$

The dependence of the velocity of the relative motion of gas bubbles on the diameter d_b indicates the influence of the physico-chemical parameters of the liquid phase. In the first approximation, it is possible to indicate the dependence of the coefficient ξ on the Reynolds number:

$$\mathrm{Re} = \frac{w_{rel} d \rho}{\mu} , \tag{5}$$

where d is the equivalent diameter of the bubble, m; μ is the coefficient of dynamic viscosity of the medium, Pa*s.

The above-mentioned equality $P_{Ar.} = P_{r.f.}$ leads to the condition $w_{rel} = const$, and the equilibrium of the resistance forces of the medium in relation to the whole complex to the law of equality of action and counteraction means a force action on the liquid phase, which leads to the formation of circulation circuits. This means that the absolute rate of emersion of gas phase must be expressed in terms of the sum w_{rel} and the rate of the liquid phase in circulation circuits $w_{liq.ph.}$

$$w_{abs} = w_{rel} + w_{liq.ph.} . \tag{6}$$

The relative velocity is close to the rate of renewal of liquid films on the surfaces of phase separation and determines the intensity of the mass transfer processes. It is obvious that the shape of the surfaces of gas bubbles is one of the factors of influence on them.

Spherical shapes are the minimum surfaces of bubbles, and to create them, the least energy is needed. However, under the action of the forces of resistance of media, they are transformed into forms of ellipsoids, which leads to an increase in interphase surfaces. It is obvious that the rate of gas bubbles deformation is related to the rate of their emersion. From this point of view, it makes sense to assess the influence of hydrostatic pressures on relative velocity w_{rel}.

Relative changes in the volumes of individual spherical gas bubbles from values V_{b1} to V_{b2} can be applied to the whole array of them characterized by the ratios:

$$V_b = \pi d^3/6; \quad S_b = \pi d^2 . \tag{7}$$

In the isothermal process, we have:

$$V_{b2} = \frac{P_1 V_{b1}}{P_2} ; \tag{8}$$

$$\frac{1}{6}\pi d_2^3 = \frac{P_1 \frac{1}{6}\pi d_1^3}{P_2}; \quad d_2 = d_1 \sqrt[3]{\frac{P_1}{P_2}} , \tag{9}$$

the ratio of the surface areas being:

$$\frac{1}{6}\pi d_2^3 = \frac{P_1 \frac{1}{6}\pi d_1^3}{P_2}; \quad \frac{S_{b2}}{S_{b1}} = \left(\sqrt[3]{\frac{P_1}{P_2}}\right)^2 . \tag{10}$$

As for the changes in hydrostatic pressures, we get:

$$d_2 = d_1 \left(\frac{mgH_{(п)}}{mgH}\right)^{1/3} = d_1 \sqrt[3]{\frac{H_{(п)}}{H}} , \tag{11}$$

where $H_{(i)}$ is the initial height of the liquid phase layer over the bubble; H is the fluid height (coordinate) of the bubble.

With the given ratios, the dependence (4) is transformed into a form:

$$w_{rel} = \sqrt{\frac{32 \rho g d_{(i)} \sqrt[3]{\frac{H_{(i)}}{H}}}{3\xi}} . \tag{12}$$

The logical adequacy of the result obtained is confirmed by comparing the expressions by which the Archimedean forces and the forces of resistance of the medium are determined, since the former are proportional to the determining size (the diameter) cubed, and the latter are proportional to the diameter squared.

The tendency of the gas phase volume to increase and the rate of its emersion lead to an increase in velocities in gas-liquid circulation circuits. The same holds true for the liquid phase and means the presence of its acceleration and the forces of inertia. The latter counteract the acceleration and increase in speed.

Thus, the energy potential of the gas phase is transformed into the kinetic energy of the liquid flow in the circulation circuits, and this transformation is accompanied by inertial power effects on the dispersed gas phase.

These features of the gas and liquid phases lead to the conclusion about the variable multiple-elevation character of interactions and the importance of creating circulation circuits. The latter is connected, firstly, with the homogenization of the medium and, secondly, with the creation of saturation and desaturation zones of the liquid phase. In the ascending parts of circulation circuits, as the hydrostatic pressures decrease, active desaturation takes place, while the saturation of the medium is maintained on CO_2. In the downcoming parts of such circuits, the possibilities of saturation are renewed.

In other words, the combination of a potential gravitational field and a generated potential field of inertial forces creates conditions for the variables of the resulting Archimedean forces:

$$\overline{R}_{Ar.} = \rho(\overline{g} \pm \overline{a})V_g, \qquad (13)$$

where a is the liquid phase acceleration in the circulatory circuit;

V_g is the total volume of the dispersed gas phase.

The effects of liquid phase accelerations manifest themselves due to variable velocities in circulation circuits in relation to the acceleration values. So the free fall mode of a gas-liquid medium is technically achievable if the condition $|\overline{g}| = -|\overline{a}|$ is fulfilled ensuring $\overline{R}_{Ar.} = 0$. By the way, it is worth noting that only in the fall mode of a gas-saturated medium, it is possible to achieve its desaturation according to the saturation index under the influence of the gravitational field. Thus, the acceleration value in (13) allows determining the resulting value $R_{Ar.}$ by the volume of the flow of the medium V_{flow} and its gas-holding ability V_g.

Let us illustrate this using the displacement of the gas-liquid flow in the conical diffuser as an example (Fig. 1).

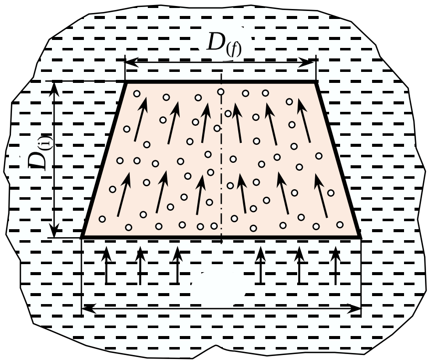

Fig. 1. Scheme for determining the hydrodynamic parameters of the gas-liquid flow

With the gas-liquid flow V_{flow}, when it enters the diffuser and when it goes out of it, we obtain these velocities:

$$w_{en} = \frac{4V_{flow}}{\pi D_{(i)}^2} \quad and \quad w_{out} = \frac{4V_{flow}}{\pi D_{(f)}^2}. \qquad (14)$$

With a conical shape of the diffuser, the acceleration in each section will be the same:

$$a = \frac{w_{out} - w_{en}}{\tau_{(f)}}, \qquad (15)$$

and the time $\tau_{(f)}$ in which each particle of a stream passes through the diffuser is found through the average velocity:

$$w_{av} = \frac{w_{en} + w_{out}}{2}. \qquad (16)$$

The following substitution makes it possible to write down:

$$w_{av} = \frac{2V_{flow}}{\pi D_{(i)}^2} + \frac{2V_{flow}}{\pi D_{(i)}^2} = \frac{2V_{flow}}{\pi}\left(1/D_{(i)}^2 + 1/D_{(f)}^2\right). \qquad (17)$$

Taking into account the height h of the diffuser, we obtain the final time $\tau_{(f)}$:

$$\tau_{(f)} = \frac{h}{w_{av}} = \frac{\pi h}{2V_{flow}\left(1/D_{(i)}^2 + 1/D_{(f)}^2\right)}. \qquad (18)$$

From here, we finally get :

$$a = \frac{\Delta w}{\tau_{(f)}} = \frac{gV_{flow}^2\left(1/D_{(f)}^2 - 1/D_{(i)}^2\right)^2}{\pi^2 h}. \qquad (19)$$

When the diffuser is oriented as shown in the figure, the velocity and acceleration are unidirectional, which allows writing down:

$$R_{Ar.} = \rho \left[g - \frac{g V_{flow}^2 \left(1 / D_{(f)}^2 - 1 / D_{(i)}^2 \right)^2}{\pi^2 h} \right] V_{г}, \quad (20)$$

and for a redirected diffuser, we get:

$$R_{Ar.} = \rho \left[g + \frac{g V_{flow}^2 \left(1 / D_{(f)}^2 - 1 / D_{(i)}^2 \right)^2}{\pi^2 h} \right] V_{г}, \quad (21)$$

According to the condition (20), the difference between the free fall acceleration and the flow movement acceleration is decisive. With certain parameters, this difference can become negative, which means changing the direction of the gas phase displacement. When the values g and a are equal, the displacement of the gas phase stops. This is a case when the velocity of relative motion w_{rel} and of mass exchange modes can be influenced.

The intensity of circulation circuits and media's homogenization level are derived from the gas-holding capacity. In anaerobic conditions, the rate of synthesis of CO_2 is determined by technological programs, and this indicator, generally, does not depend on the ratio of media's geometric parameters. However, in isovolumetric media, an increase in height leads to an increase in gas-holding capacity and intensification of gas-liquid circulation circuits. In aerobic media, the entering aeration air flows are regulated depending on the needs of biological synthesis, and the models of hydrodynamic parameters must be based on the velocity. The latter is determined by the ratio of the gas flow $V_{r.g.}$ (m^3/s) to the cross-section area of the fermentation apparatus F (m^2):

$$w_{s.} = \frac{V_{r.g.}}{F}, \text{ m/s.} \quad (22)$$

It is important that, under such conditions, the introduction of the gas phase into the medium is carried out at a fixed level, whereas under anaerobic conditions the synthesis of the dispersed gas phase is carried out throughout its entire height.

The latter means that, under such conditions, the gas-holding capacity increases almost linearly along the height of the medium, and some nonlinearity is associated with an increasing level of circulation. It is obvious that the circuit structure is non-deterministic, but there is a technical possibility to make this part of the phenomenon deterministic and adjustable (Fig. 2). For this purpose, the fermentation apparatus is equipped with a circulation tube 2 and a gas circuit 5 to create an effect of the airlift pump. This circulation circuit has three positive features. Firstly, the circuit is deterministic and adjustable. Secondly, it eliminates the problem of no circulation of the medium in the lag-phase and postfermentation modes and provides homogenization of the medium by different parameters including temperature. And, thirdly, there appear zones of the medium's active desaturation on the ascending region due to the hydrostatic pressure decrease, and those of saturation at the downcoming part due to the pressure growth.

Such transition of the medium from the ascending zone to the downcoming zone does not only intensify the mass exchange between the microorganisms, the liquid phase, and the gas phase, but also leads to using the multiple-elevation (hydrostatic) gradient according to the level of saturation of the liquid phase with CO_2, since the desaturation of the liquid in the circulation tube results in self-organized circulation in the circuit.

An excessive amount of synthesized carbon dioxide is let out through the shut-off valves by the command of the pressure regulator 4.

Approbation of the research results took place in the industrial conditions in the champagne factory 'Stolichny' (Kyiv) by implementing the scheme in Fig. 2 on one of the acratophores. The primary impuls in the organized circulation system provided a reduction of the lag-phase time by 2.5 times, which was monitored by the pressure indications in the supra-liquid volume of the gas phase. At the stage of basic fermentation, the intensity of the process grew due to the effect of the medium saturation gradient by CO_2 according to hydrostatic pressure.

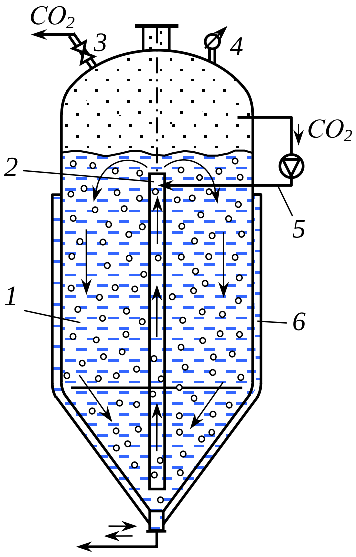

Fig. 2. Scheme of the fermentation apparatus: 1 – cylindrical conic body; 2 – circulation pipe; 3 – stop valves; 4 – pressure regulator; 5 – gas circuit with compressor; 6 – cooling jacket

Conclusions

1. The energy potential of gas-liquid media is created on the basis of gas phase dissolution in a liquid phase and the synthesis of a dispersed gas phase. These two reasons are interconnected, but their manifestations are different. The presence of a dispersed gas phase, regardless of the form of its occurrence, means the presence of a driving factor in the creation of circulatory circuits, whereas the

presence of the dissolved gas phase is only a primary reason for the formation of the dispersed gas phase. In anaerobic processes, the gas phase is represented by carbon dioxide, and in aerobic processes, it is represented by air or nitrogen from the composition of air and CO_2.

2. The driving potential of circulation circuits is determined by the gas-holding capacity of the media, which depends on the intensity of the dispersed gas phase synthesis, the geometry of the volumes of media and apparatus, and the physical properties of the phases.

3. The gradient of the level of saturating the liquid phase by the gas phase is determined by the physical and chemical properties of the latter and hydrostatic pressures of the liquid phase, and the boundary saturation depends on the pressure of the gas phase in the supraliquid volume and on the hydrostatic pressure.

4. It has been shown that a factor of intensifying the mass-exchange processes is the relative velocity of gas phase bubbles. Calculation formulae have been obtained to assess the gas-holding capacity and the driving factor as the resultant of Archimedean forces.

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