Hydrodynamics and mass transfer in a bioreactor with gas-to-liquid supply from the vortex cavity

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Abstract. The results of the study of hydrodynamic and mass transfer parameters of a stirred bioreactor during gas dispersion from the cavity of an open vortex to the area with reduced pressure in the liquid behind the impeller paddles are presented. New data were obtained on gas content, dispersed composition of gas bubbles, stirring power, and intensity of mass transfer in the air-water system, aqueous solutions of sucrose and glycerol of various concentrations and with different content of surfactants. The dependence of the stirring power on the gas content and Reynolds number, as well as the mass transfer coefficient on the boundary surface and energy dissipation, have been established. It is assumed that when calculating the dissipation of energy spent on developing a boundary surface, it is necessary to take into account the influence of viscous friction forces in the liquid. Dispersion of gas into liquid through an open vortex cavity in a stirred bioreactor allowed to increase the gas content, the boundary surface and to intensify mass transfer compared to conventional aeration systems.

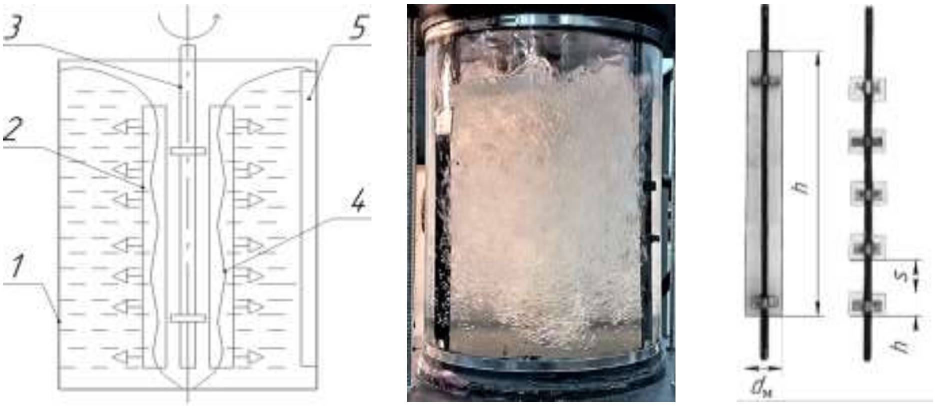
1 Introduction

Nowadays, to intensify mass transfer in gas-liquid bioreactors, a number of systems for gas saturation of culture broth have been developed and applied, among which the stirred bioreactors have found the largest application. When such bioreactors are supplied with spargers, the oxygen transfer rate increases up to 7.0 kg/(m3·h), the mass transfer coefficient is 800 h-1, the specific air consumption is 40.0 m3/kg, and the energy consumption is 2.0-3.0 kW·h/kg [1]. Although, the introduction of draft tubes in stirred bioreactors provides intensification of mass transfer [2-5], it results in increase in energy costs and complicates their design. The installation of several stirrers on the shaft of a draft tube for capturing the gas substrate from the vortex cavity and its further transition into the liquid has not found widespread use due to relatively high energy costs. When a gas phase is injected to the liquid through the surface vortices [6-10], due to maintaining low stirring speeds, a low gas content not exceeding 0.1 is ensured, and the mass transfer coefficient is amounted to 360 h-1. The most effective way to supply gas to a liquid is to place a self-inducing impeller in the bioreactor, which allows excluding gas compression facilities from the system [11-16]. The disadvantage of such an aeration system is the small depth of impeller immersion into the liquid to ensure a sufficient pressure drop in the gas cavity [17]. The complex design of the impeller causes relatively high energy costs for stirring. To address the mentioned drawbacks, a method for saturation of liquid with gas has been developed [18]. Specifically, according to the method, a hollow gas vortex maintained over the entire height of the liquid layer in the apparatus (Fig. 1a), and a reduced pressure provided in the liquid behind the impeller paddles, which ensures the introduction of gas from the gas vortex into the liquid with the formation of a gas-liquid mixture with a developed boundary surface contact. According to the early studies, gas saturation in an apparatus with a paddle impeller was provided by rotation of the liquid at an angular velocity of 7-11 rad/s and achieving an agitation speed of more than 550 rpm [19]. In this case, formation of the gas vortex with the required dimensions was ensured by mounting partitions on the wall of the apparatus, which allowed retaining liquid on the surface of the impeller paddles, creating a hollow gas vortex and providing an area with reduced pressure in the liquid behind the rotating impeller paddles. The advantage of this saturation method is the provision of a developed boundary surface contact [19], as well as a simple design of the impeller, which consists of two or more paddles made of rectangular plates mounted on the shaft of the apparatus.

The aim of this work was to study the hydrodynamic and mass transfer parameters of gas-liquid rotating flows of water and aqueous solutions of sucrose and glycerol of different viscosities and surface tension coefficients when supplying a gas from the cavity of an open vortex into a liquid behind the rotating impeller paddles.

2 Results

A general view of the test model of the bioreactor is shown in Fig. 1. The vessel was made of transparent material and had an internal diameter of 0.28 m and 0.54 m, and the length was 0.3 m and 1.5 m, respectively. Most of the research was carried out on a two-bladed stirrer with a diameter of 0.06-0.115 m. The width of the partition installed on the bioreactor shell was 0.025 m and it was placed over the entire height of the liquid column in the apparatus. When placing several stirrers on the shaft (Fig. 1d), the height of the paddle was h = 0.05 m, and the spacing between the paddles was s = 0.125 m.



a b c

Fig. 1. Scheme of gas-to-liquid dispersion (*a*), general view of the experimental bioreactor (*b*) and placement of paddles on the stirrer shaft (*c*): (*a*) 1 – bioreactor shell; 2 – impeller paddles; 3 – stirrer shaft; 4 – vortex cavity; 5 – partition.

As model liquid media, water, sucrose-water, and glycerin-water solutions were used. Physical characteristics of the studied liquids are shown in Table 1.

Table 1. Physical characteristics of the studied liquids.

Medium	**T, ˚C**	**P_{cm},kg/m^3**	**$\mu\cdot10^3$, Pa·s**	**σ, kg/s^2**
Water	10-60	1000-983	1.3-0.47	0.076-0.066
Sucrose-water (20%)	23	955.0	1.7	0.073
Sucrose-water (25%)	23	977.5	2.0	0.071
Sucrose-water (35%)	23	1039.5	3.1	0.070
Glycerin-water (5%)	20	1140	1.0	0.074
Glycerin-water (15%)	20	1034	1.52·	0.073
Glycerin-water (20 %)	20	1047	1.76·	0.072
SAA* (0.1%)	24	997	0.9·	0.069
SAA* (0.0025%)	24	998	0.9·	0.058
SAA* (0.0005%)	24	999	0.9·	0.047

* SAA - Sodium dinatrium lauryl sulfosuccinate

The gas content in the liquid was determined volumetrically according to the formula:

$$\varphi = (Hg\text{-}l - H)/Hg\text{-}l\,, \tag{1}$$

where H – height of the liquid column in the apparatus, m; Hg-l – height of gas-liquid column, m.

The average surface diameter of a gas bubble was determined using photography with further calculation according to [20, 21]:

$$d_b = \sqrt{\frac{\Sigma(N_{bi}\cdot d_{bi}^2)}{\Sigma N_i}}\,, \tag{2}$$

where Nbi – a number of bubbles of a certain size; dbi – bubble diameter, m.

The boundary surface was determined according to the following formula:

$$a = 6\varphi/db, \tag{3}$$

where φ – the gas content; db – the average surface diameter of a gas bubble, m.

Mass transfer at a stage was studied using the absorption of air oxygen by water as an example. Degassing of air from aqueous solutions was carried out by stirring under vacuum.

The mass transfer rate was determined based on the ideal mixing model [22]:

$$\beta = \ln[(1- c/c^*)/A]/\tau, \tag{4}$$

where c0 – initial concentration of oxygen in the liquid, kg/m3; c – final concentration of oxygen in the liquid, kg/m3; c* – equilibrium concentration of oxygen in the liquid, kg/m3; τ – time, s.

The value of coefficient A is determined at c = c0 and τ = 0.

Energy dissipation ε (W/kg) was calculated using the formula:

$$\varepsilon = N/m\,, \tag{5}$$

where N – stirring power, W; m – weight of liquid, kg.

Power criterion for stirring power was determined as:

$$KN = N/\cdot\rho cm\cdot n3\cdot dm5, \tag{6}$$

where KN – power criterion; N – stirring power, W; ρcm – density of a gas-liquid mixture, kg/m3; n – rotation frequency, s-1; dм – diameter of the impeller, m.

Density of a gas-liquid mixture was determined as:

$$Pcm = \rho l\cdot(1-\varphi) + \rho g \cdot \varphi, \qquad (7)$$

where ρl – density of liquid, kg/m3; φ – gas content; ρg – density of air, kg/m3.

Stirring power was determined from the measured values of current and voltage.

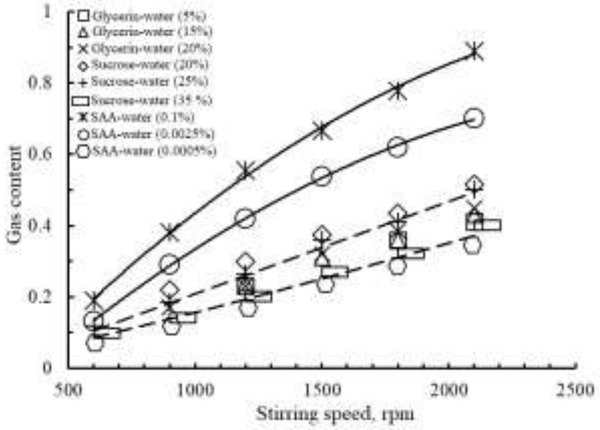
Reynolds number was determined according to the formula:

$$Re = (n\cdot dm2\cdot \rho cm)/\ \mu, \qquad (8)$$

where n – rotation frequency, s-1; dm – diameter of the impeller, m; ρcm – density of a gas-liquid mixture, kg/m3; μ – coefficient of dynamic viscosity of the medium, Pa·s.

The surface tension was determined by the maximum bubble pressure method.

Typical results of studying the gas content in the apparatus are presented in Fig. 2. When air was dispersed into the water, the gas content (Fig. 2b) reached 0.25, whereas in apparatuses with a self-inducing impeller or circulation tubes the gas content usually does not exceed 0.15. When studying aqueous solutions of sucrose and glycerol, the gas content significantly increased up to 0.45 (Fig. 2a) as a result of high energy dissipation due to increase in the dynamic viscosity of the solutions. When a surfactant was added to water (Table 1), the gas content was significantly higher (Fig. 1a).



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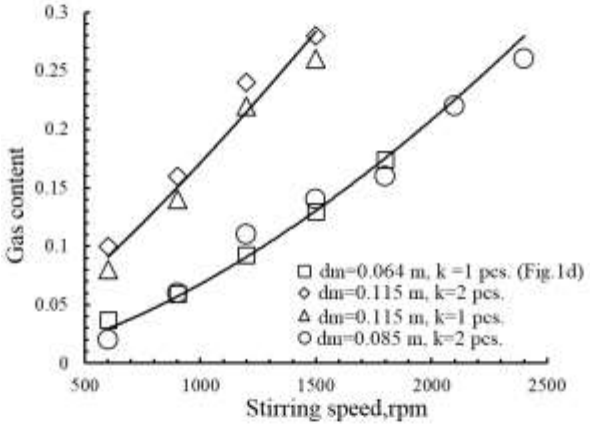

b

Fig. 2. Dependence of gas content on the stirring speed when the liquid temperature is 20-24ºC: (*a*) at D = 0.28 m and h = 0.3 m, d_m= 0.064 m; (*b*) D = 0.54 m and h = 0.5 m, water.

As has been found, gas content increases along with increase in stirring speed, diameter of the impeller, number of paddles and their length. This corresponds previously published data [18, 19] and is due to an increase in the pressure drop in the liquid behind the impeller.

Photographic recording of the gas-liquid medium followed by measuring the sizes of gas bubbles allowed establishing their size distribution (Fig. 3). According to the data (Fig. 3a), the diameter of the bubbles decreases with an increase in dynamic viscosity of the liquid. Specifically, for water medium, the majority of bubbles have a diameter of 2-3 mm, whereas in an aqueous solution of sucrose, the diameter of bubbles has decreased significantly and their maximum number is observed with a diameter of 0.05 mm. As shown in Fig. 3b, as stirring speed increases, the diameter of the bubbles decreases, which is caused by their fragmentation. For the impeller (Fig. 1d) with 50 mm paddles, positioned with an optimal spacing s = 125 mm, the majority of bubbles in the water had a diameter of 1-2 mm, which is higher than when the paddles are positioned according to the scheme shown in Fig. 1c, that is due to a higher speed of fluid circulation between the paddles. The boundary surface area, calculated according to (3), for aqueous solutions of sucrose and glycerol reached high values and amounted to more than 1200 m-1.

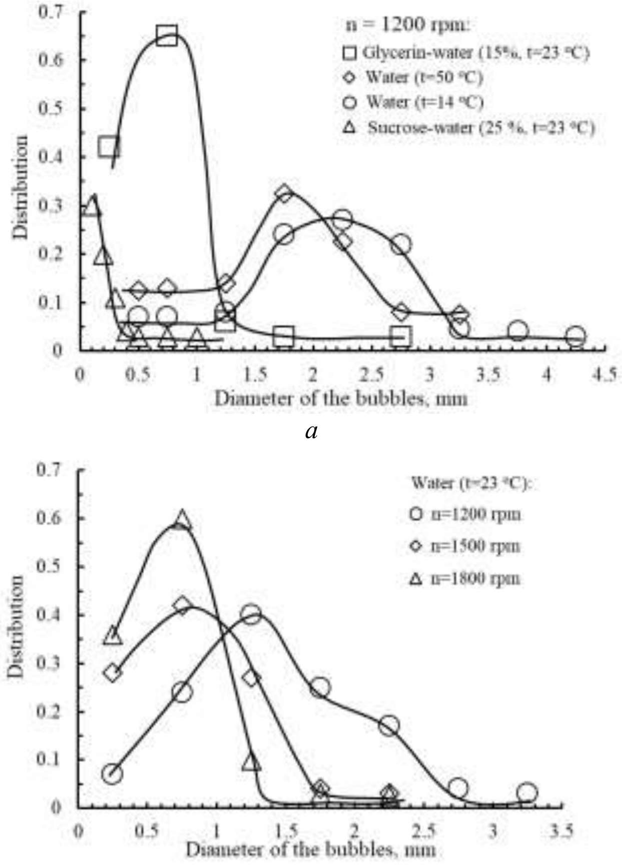

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Fig. 3. Size distribution of air bubbles in a gas-liquid mixture.

The obtained values of the stirring power spent on mixing are presented in Fig. 4. With an increase in the dynamic viscosity of the liquid and in the stirring speed, the stirring power increases, but it decreases with an increase in the gas content, which is consistent with the data [23-26].

When a surfactant is added to water, the stirring power increases (Fig. 4b), which is caused by the structure of the gas-liquid mixture.

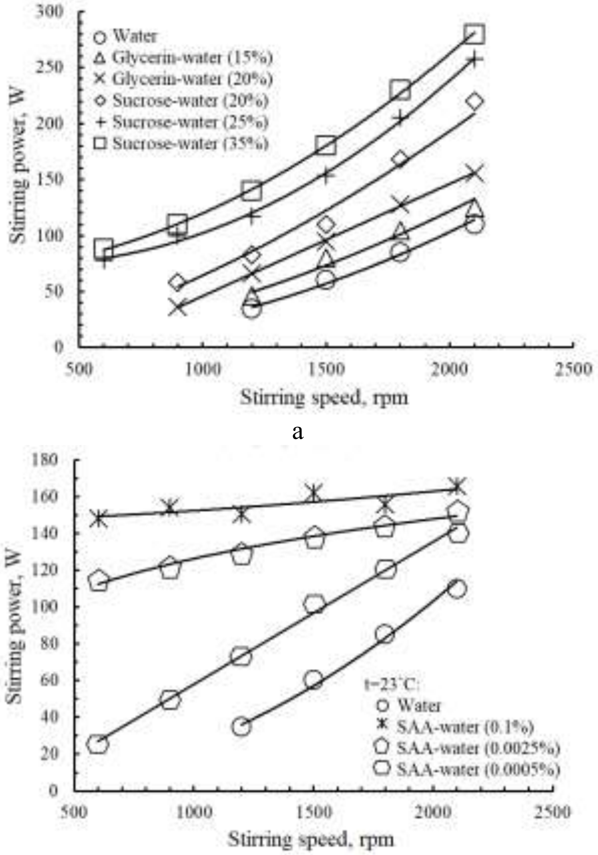

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Fig. 4. Dependence of stirring power in liquid on stirring speed at D = 0.28 m and h = 0.3 m.

The dependence of power criterion for stirring power, which is essential for calculating energy dissipation, on the gas content and Reynolds number of the stirrer are presented in Fig. 5.

It has been found that the value of the criterion depends on both the Reynolds number and the gas content and follows the pattern:

$$KN \approx Re - 0.13 \cdot \varphi - 0.9 \tag{9}$$

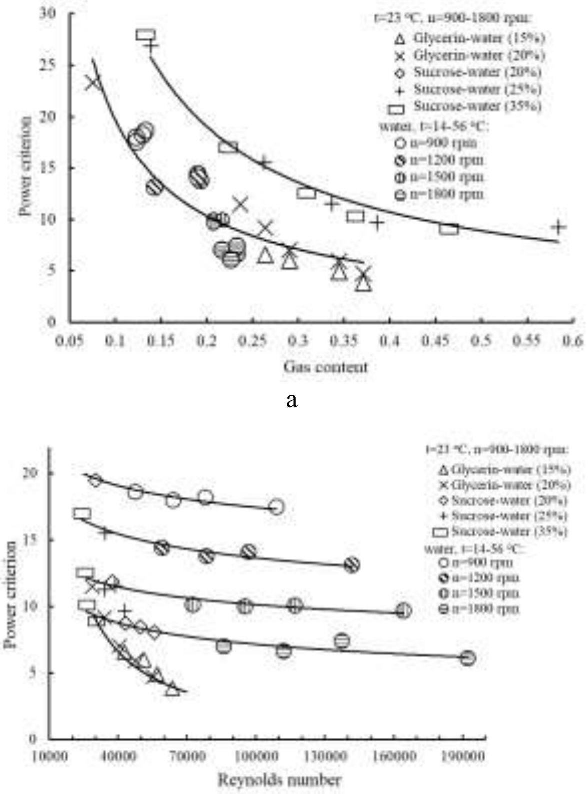

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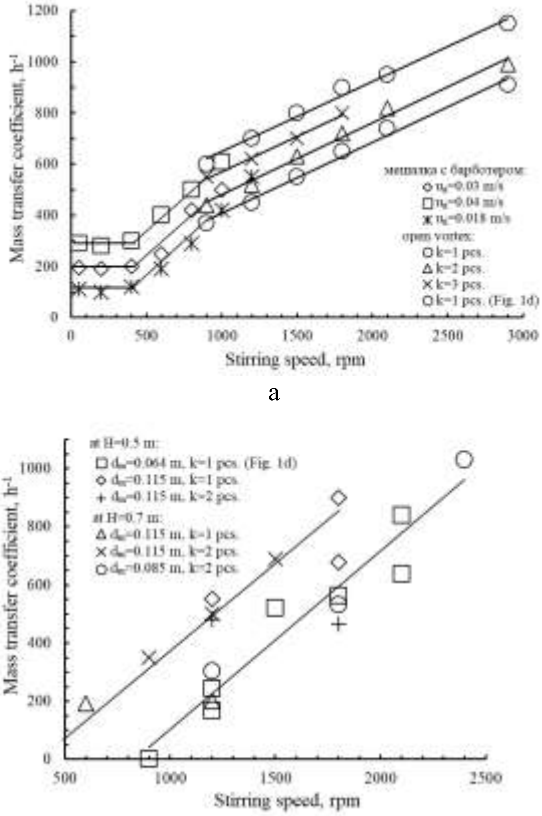
Fig. 5. Dependence of power criterion on gas content (*a*) and Reynolds number of the stirrer (*b*) at D = 0.28 m, h = 0.3 m.

A sufficient number of studies have been devoted to mass transfer in an apparatus with a stirrer. It has been established that the value of the mass transfer coefficient depends both on energy dissipation and on the diameter of a gas bubble and gas content [2, 13, 16, 27]. The characteristic dependence for the mass transfer coefficient obtained in this study on the air-water system are presented in Fig. 6, where the data obtained in a bioreactor with a turbine impeller and a sparger are also plotted (points 1-3) according to [28]. It has been found that mass transfer increases with an increase in the height and a number of paddles, the diameter of the impeller and stirring speed, which is consistent with the data calculated from the dependence previously obtained [19].

$$\beta = A\cdot[\varepsilon 0.6\cdot a0.8]0.455\,, \qquad (10)$$

where β – mass transfer coefficient, h^{-1}; A=30 – coefficient; *a* – boundary surface, m^{-1}.



a

b

Fig. 6. Dependence of mass transfer in the air-water system on the stirring speed: (*a*) at D = 0.375 m; (*b*) at D = 0.54 m.

Experimental values of mass transfer coefficient in an apparatus with a stirrer, obtained for water with surfactants and water solutions with different viscosities, depending on energy dissipation are presented in Fig. 7. With an increase in dynamic viscosity of the solution, the mass transfer decreases. In some cases, mass transfer was greater for water due to high energy dissipation and boundary surface. With increase in surfactant concentration in water, the mass transfer increases due to an increase in the boundary surface.

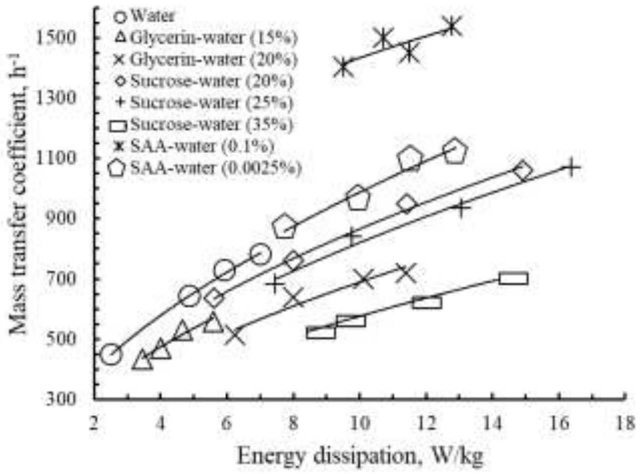


Fig. 7. Dependence of mass transfer on energy dissipation.

3 Conclusion

The processing of experimental data (Fig. 7) considering not only energy dissipation, but also the boundary surface, is presented in Fig. 8. It was found that with an increase in dynamic viscosity of the solution, the value of mass transfer coefficient, despite the increase in the boundary surface and energy dissipation, decreases compared to the data obtained for water (line 1 in Fig. 8). This is due to neglecting energy consumption to overcome the force of viscous friction in a rotating gas-liquid flow when calculating energy dissipation [29].

An increase in surfactant content in a liquid leads to an increase in stirring power (Fig. 4b) due to a change in the structure of the gas-liquid layer in the apparatus, which leads to a decrease in mass transfer compared to the data obtained for water.

To calculate the mass transfer coefficient according to equation (10) at values of dynamic viscosity coefficient (μ) in the range of (1.2-1.8) ·10-3 Pa·s, the coefficient must be taken equal to A = 19 (line 2 in Fig. 8), and at μ = 1.9-3.1 Pa·s, A = 16 (line 3, Fig. 8).

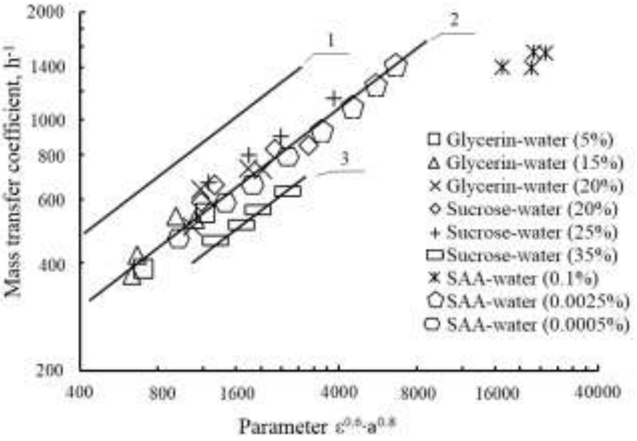


Fig. 8. Dependence of mass transfer coefficient on $\varepsilon^{0.6} \cdot a^{0.8}$.

As a result of the studies carried out in an apparatus with the stirrer during the supply of gas from the vortex cavity into the liquid behind the impeller, new data were obtained that expand the possibilities of using gas-liquid bioreactors with stirring devices. For the first time, the dependence power criterion for stirring power on the gas content and Reynolds number is shown. The dependence for calculating the value of the mass transfer coefficient in liquids with different viscosities has been refined.

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