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Vortex apparatus for gas-liquid systems

Bakhronov Khoshim Shayimovich, Tuyboyov Oybek Valijonovich,
Ganiyeva Saboxat Uktamovna, Khudoyberdiyeva Nazora Sharofovna

Doctor of technical Science, Chemical technology department of Navoi State Mining Institute, Navoi city, Uzbekistan
Senior researcher of Chemical technology department of Navoi State Mining Institute, Navoi city, Uzbekistan
Senior lecturer of Chemical technology department of Navoi State Mining Institute, Navoi city, Uzbekistan
Head of Department of Computer halls of Navoi State Mining Institute, Navoi city, Uzbekistan

ABSTRACT: this paper presents results of experimental studies of hydrodynamics, flow structure, and mass transfer in a vortex apparatus with a swirling gas flow device having involutes shaped channels. The results of experiments on the flow regime of the gas-liquid flow, hydraulic resistance, gas contenting, interfacial surface and the mass-transfer coefficient do not contradict the literature data. It is established that the use of vortex contact devices in mass-transfer devices allows significantly intensifying mass-transfer and increasing gas productivity.

KEYWORDS*:* plate columns, gas velocity, vortex apparatus, rotating gas flow, contact device, swirled, bubble diameter, flow regimes, interfacial surface, hydraulic resistance, critical gas velocity, mass transfer coefficient.

I. INTRODUCTION

Rapidly development of chemical and petrochemical industry necessitated a sharp increase in the productivity and efficiency of absorption and distillation columns. Currently used in industry, tray columns with a cross or countercurrent phase interaction have relatively low productivity and low efficiency. The permissible gas velocities (steam) in them do not exceed 1-2 m / s. A further increase in the gas velocity causes intense fluid drift and flooding of the column. In connection with this, the task of increasing the productivity of columns was solved mainly by increasing the diameter of the columns, which is hardly economically viable. Small loads on the pair caused low mass transfer efficiency.

Using of vortex devices with a rotating flow of gas allows to intensify technological processes, sometimes increasing the specific productivity by 1-2 orders of magnitude, and also to combine several processes in one apparatus. Centrifugal-bubbling devices for cleaning gases from dust and additional purification of ventilation emissions by increasing the contact surface of phases and heat-exchange coefficients by 5-10 times in comparison with conventional bubbling ones allow reducing the size and metal capacity of the equipment by the same factor. However, the improvement of the considered devices with the purpose of increasing their productivity is hampered by insufficient knowledge of the processes taking place on the contact device.

Main requirements for the construction of vortex contact devices for gas-liquid systems is to provide a developed interfacial surface, achieve high turbulence of flows and fluid retention at relatively low hydraulic resistance and a large gas load, which can be achieved by uniformly dispersing the gas into a liquid and creating conditions for the rotational motion of the gas-liquid mixture in the apparatus.

II. METHODS

A research of vortex apparatus with a swirler, which has an involutes shaped channel for swirling the flow, was performed on an air-water system. The diameter of the apparatus was D = 100 mm, and the diameter of the swirler $D_з$=88 mm. The geometric parameters of the investigated swirlers are given in the table.

Gas flow rate changed from 0 to 500 meter^3 / hour and was measured by a normal diaphragm, and the water flow from 30 to 180 kg / hour, which corresponded to a linear irrigation density from 100 to 600 kg / (meter · hour), was

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measured by rotameters. The range of the investigated liquid and gas temperatures was from 10 to 20 °C, the density of the liquid is 1000 kg / m^3, the coefficient of dynamic viscosity of the liquid is (1,3-1) • 10^{-3} Pascal • second. The pressure drop across the stage was measured by a differential pressure gauge.

Table

Geometric parameters of the studied swirlers.

Type of swirler	Slot height, h, mm	Slot width, b, mm	Slot area, $F_{щ}$, mm^2	Number of slots, n, piece	Geometric characteristic the swirler, Γ
Э1	200	19,6	3925	2	2
Э2	100	15,7	1570	2	5
Э3	80	9,8	785	2	10
Э4	50	9,8	491	2	16

Average surface diameter of the gas bubbles was calculated by processing photos of the gas-liquid layer according to the formula:

$$d_{п}=(\Sigma n_{i}\cdot d_{i}^{2}/\Sigma n_{i})^{0,5} \tag{1}$$

The gas fraction in the bulk of the liquid was determined according to [1]:

$$\varphi=(V_{гж}-V_{ж})/V_{гж} \tag{2}$$

The interfacial surface was calculated from the relation, $a=6\varphi/d_{п}$.

The calculated bubble diameter was calculated by the equation [2]

$$d_{п}=3,48\cdot(\sigma_{ж}^{3}/\xi^{3}\cdot\rho_{ж}^{3}\cdot\varepsilon^{2})^{1/5} \tag{3}$$

Dissipation of energy entering into equation (3) was calculated from the formula $\varepsilon=E_{вн}/m$, where the energy consumption for overcoming the internal friction forces $E_{вн}$ was determined according to [3]:

$$E_{вн}=Q_{г}\rho_{г}w_{г}^{2}/2+Q_{ж}\rho_{ж}H_{ж}g-Q_{гж}\text{-}\rho_{гж}H_{гж}g\text{-}J\omega^{2}/2-\tau_{гж}fR\omega \tag{4}$$

Angular velocity of the gas-liquid layer was determined by a specially manufactured Pitot-Prandtl tube. The oxygen concentration in the water was determined by a sensor of the polar type graphic type.

The mass transfer coefficient in the liquid in the apparatus was calculated from the dependences obtained on the basis of the ideal mixing model.

$$dc/d\tau=(L/V)\cdot(c_{н}-c_{к})+\beta_{v}(c^{*}-c_{к}) \tag{5}$$

In the stationary regime of the mass transfer process ($dc/d\tau=0$), the calculation of β_{v} according to (5) was made from the dependence:

$$\beta_{v}=L\cdot(c_{н}-c_{к})/(-V\cdot\beta_{v}(c^{*}-c_{к})) \tag{6}$$

$$\beta_{20}=\beta_{v}\cdot(D_{20}/D_{t})^{0.5} \tag{7}$$

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III. EXPERIMENTS

On the first stage of the experiments, flow regimes and the gas-liquid flow structure were studied. Depending on the gas consumption, there are three main modes of the gas-liquid mixture in the apparatus: bubble, annular and film. For contact apparatus of apparatus working with gas-liquid systems in order to obtain a developed interfacial surface with comparatively low hydraulic resistance, the annular flow regime that is observed when the critical gas velocity at the exit from the gap is greatest is of greatest interest [4].

IV. RESULTS

In the annular flow regime, the liquid from the central part of the apparatus is extruded to the periphery by means of centrifugal forces to form a rotating gas-liquid layer in the form of a cylinder. As the gas velocity increases, the thickness of the layer decreases and its height increases. When the critical gas velocity $w_п$ (which also characterizes the beginning of the opening of the gaps for the passage of gas) is reached, a film flow regime with a separate flow of gas and liquid is observed. In this regime, the outflow of gas bubbles from the rotating liquid layer is observed and there is no updating.

At relatively low flow rates, gas jets leaving the channels of the swirler are crushed in the liquid, forming in the apparatus an aerated gas-liquid layer and a layer of stationary liquid near the swirler, which leads to the formation of stagnant zones.

When the gas velocity in the narrow section of the swirler $w_{кр}$ channel is reached, the liquid in the apparatus starts to rotate. An aerated volume with high gas content and a lower rotating layer with a volume with gas bubble less than $d_п \leq 0{,}5$ mm form, with angular velocities of the lower layer 1,4-1,8 times higher than the angular velocities of the upper layer.

When the velocity of the gas in the channel of the swirler $w=(2{,}6 \div 2{,}9)w_{кр}$ is reached, a film flow regime arises with the formation of a cavity along the axis of the apparatus.

V. DISSCUSSION

The gas velocity $w_{кр}$ at which the transition occurs to the annular flow regime can be estimated from the formula obtained from the theorem on the change in the angular momentum under the assumption that the friction against the walls is much less than the viscous friction forces and considering the liquid as a solid cylinder of mass m and radius $R_з$ [5]:

$$w_{кр}=[(\rho_ж(1-\varphi)+\rho_г\varphi)/\rho_г \cdot (R^2/R_з)\cdot 2V/f\cos\alpha]^{0,5} \qquad (8)$$

The dependence of the critical gas velocity in the channels of the swirlers on the irrigation density of the investigated swirlers is shown in *Fig 1*. As the value of the geometric characteristics of the swirlers decreases, $\Gamma=F/F_щ$, where $F_щ=b_щ \cdot h_щ$ and $F=\pi D^2/4$, the critical velocity of the gas increases.

The critical gas velocity depends on the size and number of slots and the radius of the apparatus. As can be seen, an increase in the cross-sectional area of the channels for gas passage (with a decrease in the geometric characteristic $F/F_щ$), the transition to the annular flow regime occurs at a lower gas velocity.

At the next stage of the experiments, the hydraulic resistance of the vortex apparatus was investigated. The total hydraulic resistance of the vortex apparatus with involute swirls is shown in *Fig. 2*. The comparison of the experimental data is carried out with the results of the equation:

$$\Delta P=\xi \cdot \rho_г w^2/2+\rho_ж \cdot g \cdot H \cdot (1-\varphi) \qquad (9)$$

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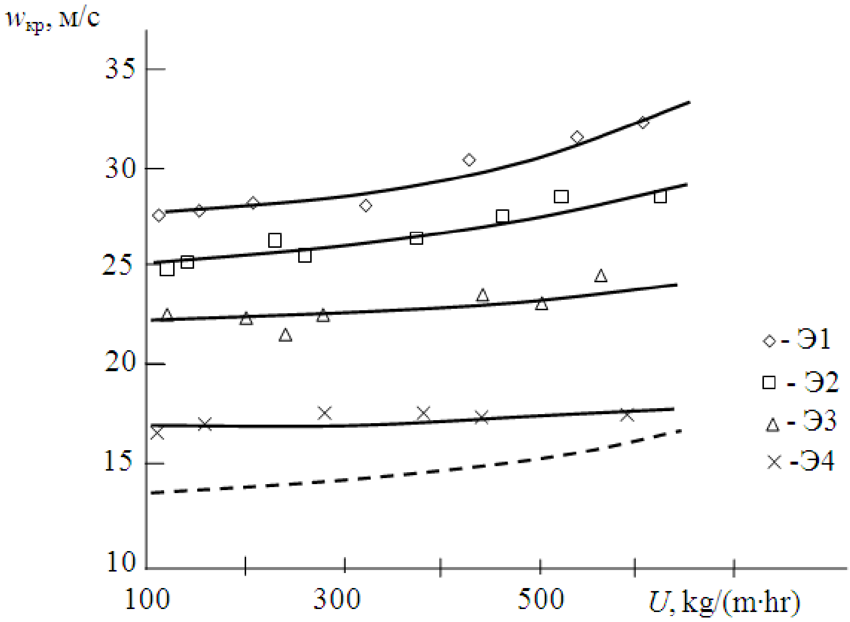

Fig. 1. Dependence of the critical gas velocity on the density of irrigation, for the vortex contact steps presented in the table. The dashed curve is the calculation by equation (8)

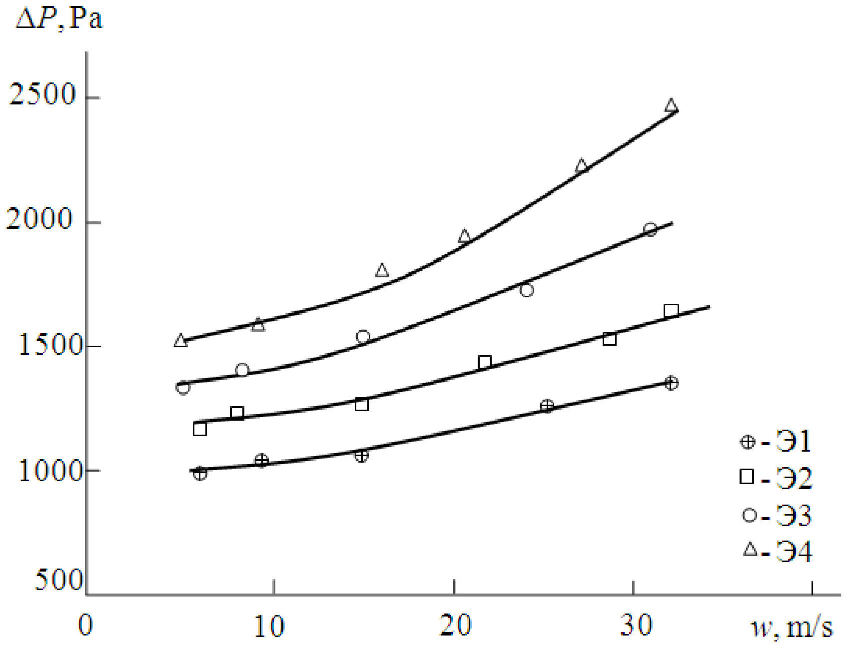

Fig. 2. Dependence of the total hydraulic resistance of the vortex apparatus on the velocity of the gas in the channels of the swirler.

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Where the value of the coefficient of resistance of dry apparatus entering into the dependence (9) is presented in *Fig. 3* and amounted to ξ = 1,1-3,2. The least resistance is possessed by a vortex apparatus with an established swirler of type Э1. The relatively high resistance of the swirler EЭ4 is due to local input and output impedances.

For all investigated vortexes, the gas fraction in the liquid was 0,2-0,4 for the annular regime and decreases with increasing gas velocity. In the film mode, the gas content is slightly dependent on the gas velocity and decreases with increasing liquid column on the contact device. In this mode, the gas content is mainly determined by the inertial layer and does not depend on the constructive performance of the swirler channels.

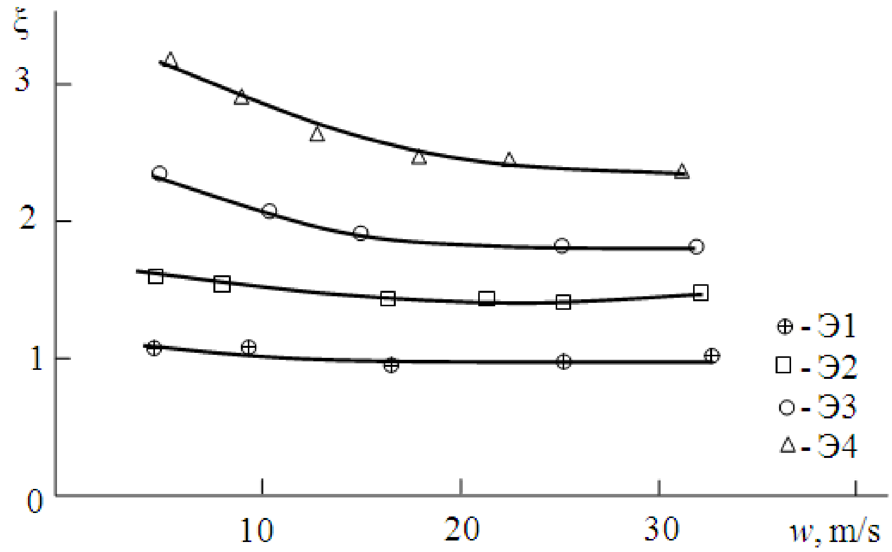

Fig. 3. Dependence of the coefficient of hydraulic resistance of dry contact steps on the gas velocity in the channels of the swirler, for the vortex contact steps presented in the table.

To calculate the value of the interfacial surface, the average surface diameter of the gas bubble was found to depend on the gas velocity in the channels of the swirler. The satisfactory convergence of the calculated $d_п$ by the equation and the experimental values in the film mode allows us to assume that in this case the crushing of the gas in the liquid on the stage is provided, in the main, by inertia forces, and the diameter of the bubble depends little on the design of the swirler.

The obtained data made it possible to calculate the interphase surface. In the annular flow regime with increasing gas velocity in the channels of the swirler and a decrease in the volume of the liquid at the contact stage, the magnitude of the interfacial surface increases (*Fig. 4*). However, in the case of film mode, the interfacial surface is slightly dependent on the gas velocity, and for all investigated contact steps it was 500-1100 mm^{-1} depending on the height of the column.

As the gas flow rate increases, the angular velocity of the gas-liquid layer on the step increases (*Fig. 5*). With a film flow, it is approximately the same for all investigated designs of swirlers, and with an increase in fluid flow, it increases insignificantly.

The characteristic dependences of the volume coefficient of mass transfer on the velocity of the gas in the channels of the swirler are shown in *Fig. 6*. Mass transfer in the film mode is practically independent of the gas velocity in the stage, which agrees with the data of [5]. In this regime, the angular velocity of rotation of the gas-liquid layer is practically the same for the same volume of liquid.

It should be noted that the use of a vortex device made it possible to increase the mass-transfer intensity by 5-7 times, and the productivity of the apparatus by gas is 6-8 times compared with a device with an irrotational contact device.

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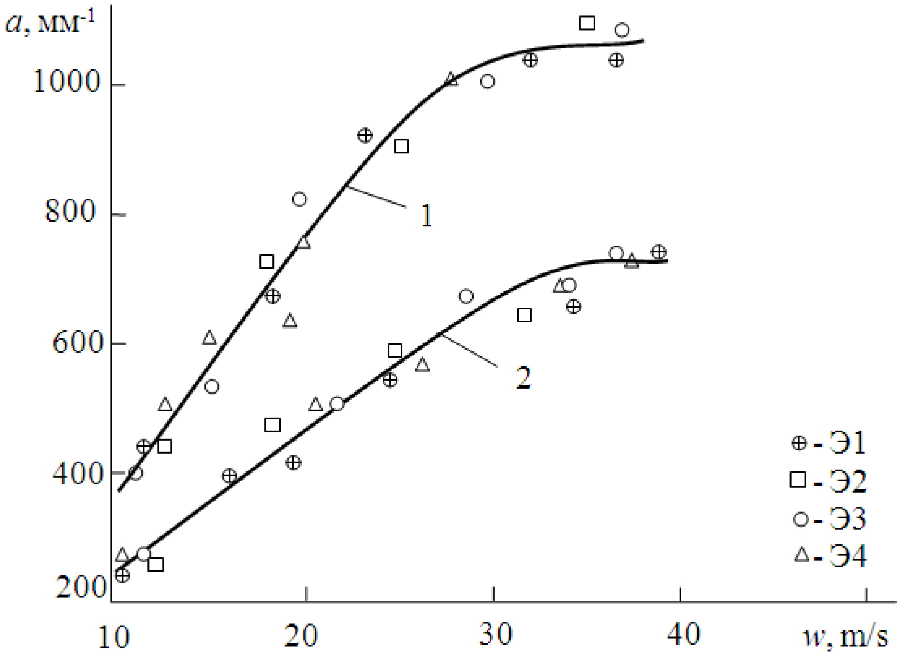

Fig. 4. Dependence of the interfacial surface on the velocity of the gas in the channels of the swirler for vortex contact steps, presented in the table: 1) V = 200 and 2) V = 600 kg / (m · h).

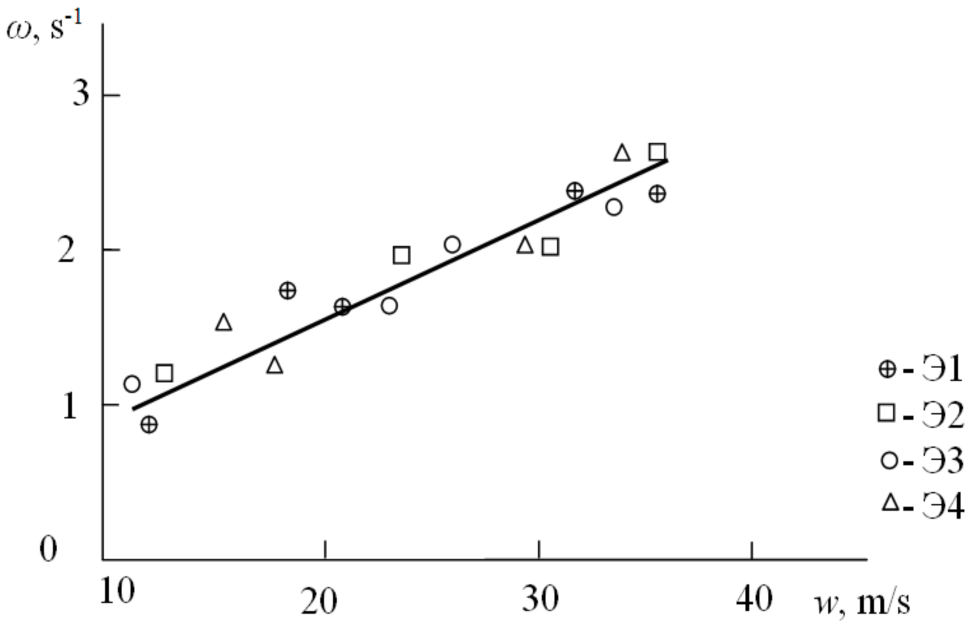

Fig. 5. Dependence of the angular velocity of the gas-liquid layer on the gas velocity in the channels of the swirler for vortex contact steps, presented in the table, V = 400 kg / (m · h).

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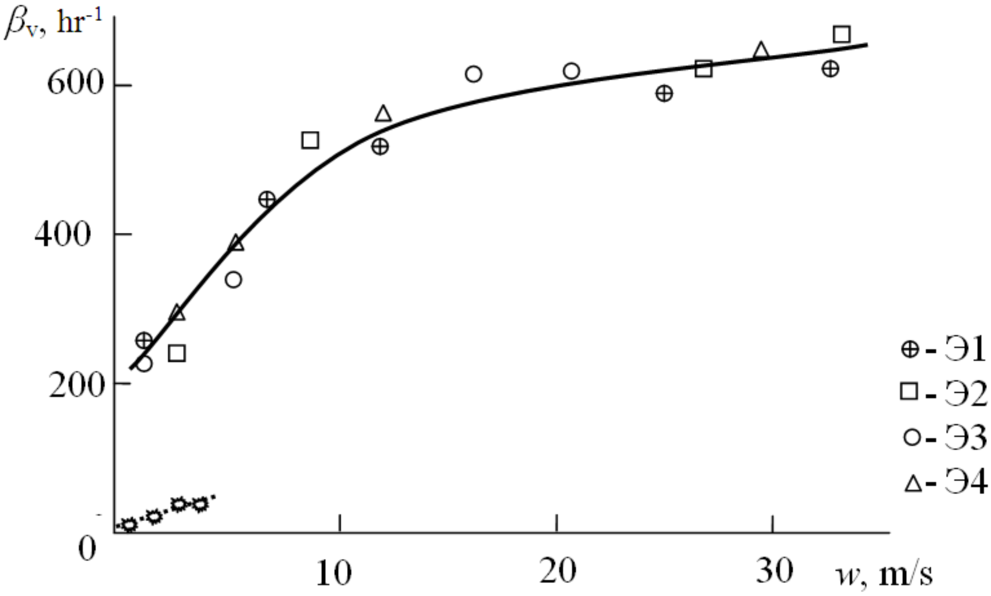

Fig. 6. Dependence of the volume mass transfer coefficient on the gas velocity in the channels of the swirler for vortex contact steps, presented in the table, V = 400 kg / (m • h). Dotted line for the flat contact apparatus.

VI. CONCLUSION

Thus, the gas content, the bubble diameter, the interfacial surface, and the volume coefficient of mass transfer of contact apparatus with tangential curlers are determined. It is shown that under the film flow regime the mass transfer coefficient is slightly dependent on the gas velocity in the channels of the swirler and the design of the vortex contact stage. The use of vortex contact apparatus in mass-transfer apparatus allows to significantly intensify mass transfer and increase gas productivity. The presented data can be used in the calculation and design of vortex contact steps.

Notation

a - Is the specific interfacial surface, m^{-1}
c - Concentration of oxygen, kg / m^3
$c_н$ - concentration of oxygen in the liquid entering the stage, kg / m^3
$c_к$ - is the concentration of oxygen in the liquid in the step, kg / m^3
c^* - is the equilibrium concentration of oxygen in the liquid, kg / m^3
D, d - is the diameter, m
D_t - is the diffusion coefficient of oxygen in water at a liquid temperature, m^2 / s
F - Is the cross-sectional area of the apparatus, m^2
$F_{щ}$ - total channel cross-sectional area, m^2
L - Liquid consumption, m^3 / s
m - Is the mass, kg
n - Number of channels; gas bubbles, pieces
H - Height of the liquid layer, m
h - Height of channels for gas passage, m
b - Channel width, m
Q - Volume flow, m^3 / s
α - Is the angle of inclination of the channel, deg

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R - Is the radius, m
w - Average flow rate of the gas in the swirler channel, m / s
ω - Angular velocity, s^{-1}
V - Volume of liquid in the stage, m^3
J - Moment of inertia, kg • m2 • s^{-1}
ε - Energy dissipation, m^2 / s^3
ρ - Density, kg / m^3
β - Surface mass-transfer coefficient, m / s
β_v - is the volume mass-transfer coefficient, s^{-1}
φ - Gas content
σ - Coefficient of surface tension, N / m;
τ - Tangential stresses, N / m^2; time, s
ξ - Is a coefficient of resistance of dry stage
Δ*P* - pressure drop, Pa

Indexes

г - Gas
кр - critical
п - Gas bubbles
с - Is a step
ж - is liquid
з -is a vortex
г-ж - gas-liquid mixture

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