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Gas-Liquid Interaction on Perforated Plates

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***Abstract*—**The paper deals with hydrodynamics of liquid-gas layers under gas streaming through liquid layer on perforated plates in column apparatuses. The plates with large apertures have been investigated especially. It was shown that hydrodynamic regularities for these plates are essentially different from known laws for foam forming on fine-perforated plates. Main regularities of liquid-gas interaction on plates with large apertures have been established.

***Keywords*—**column apparatus, large aperture**,** liquid-gas layer, perforated plate.

I. Introduction

RESULTS of researches and industrial introduction of perforated plates with large apertures testify that regularities of interactions between gas and liquid phases on plates with large and small apertures are essentially different [1, 2]. In our work distinctive features of exploration of plates with large apertures were studied in comparison with fine perforated plates in identical conditions.

The basic features of interaction of gas and liquid on similar plates are revealed. The first feature is formation of high and strongly turbulent foamy layer which structure is homogeneous because of absence of essential oscillations. The other feature is the simultaneous flow of gas and liquid streams through the same apertures in a plate. It is established also that the liquid flows in the form of streams, occupying the central part of an aperture [3, 4] that essentially differs from known laws of foam forming on fine-perforated plates.

II. Experimental Data

We carried out the comparative researches of parameters controlling the efficiency of columns with plates with large and small apertures on experimental devices of rectangular (0.15 X 0.4m), round (D_a =0.35m) and semicircular (D_a =1.0 m) sections. The essentially new two phenomena are as a result found out. They are the secondary foaming on counter-flow plates in the unknown formerly bounds of constructive and regime parameters and resonant oscillation of a layer. We studied the laws of gas flow through a liquid layer in cases of one, two and three apertures with their subsequent check at intensive bubbling. In total the one hundred two plates with diameters of apertures d_0 from 0.006 to 0.12 m and with free section S_0 =0.1—0.5 m^2/m^2 were investigated.

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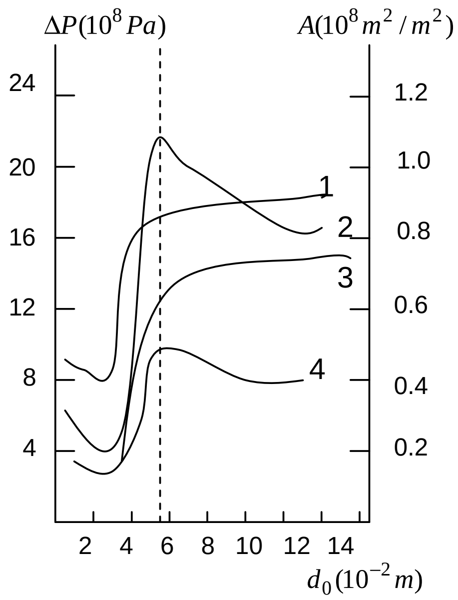
The gas velocities in an aperture and in free section of the column were into the bounds of 0.1- 40 m/s and 0.5- 4.5 m/s accordingly. Height of an initial liquid layer h_0 on a plate was changed from 0.03 to 0.3 m, and density of irrigation L_0 - from 5 to 87.5 m^3/m^{2}h.

Plots (Fig.1) show that under increasing the diameter d_0 from 0.2 to 0.3 m in a regime of formation of the foamy layer [5] the well known regularities for fine-perforated plates have been correct.



$W_g\,(m/s); L_0\,(m^3/m^2h); D_a\,(m)$: Curves 1, 2, 4- 2; 5; 0.35. Curve 3- 3; 25; 1.0

Fig.1 Dependences of the surface of phase contact (1), the height of the initial liquid layer (2) and the pressure drop (3, 4) on the diameter of an aperture

Namely, we can observe some decrease of the pressure drop ΔP , the height h_0 and the surface of phases contact A, and it leads to deterioration of the structure of the liquid layer. Owing to these reasons it was supposed formerly that the further increase of the apertures diameters was irrational. However, as it is established in our investigation the increase of d_0 after 0.3 m leads to sharp increasing both the height of the gas-liquid layer H , and the surface of phases contact.

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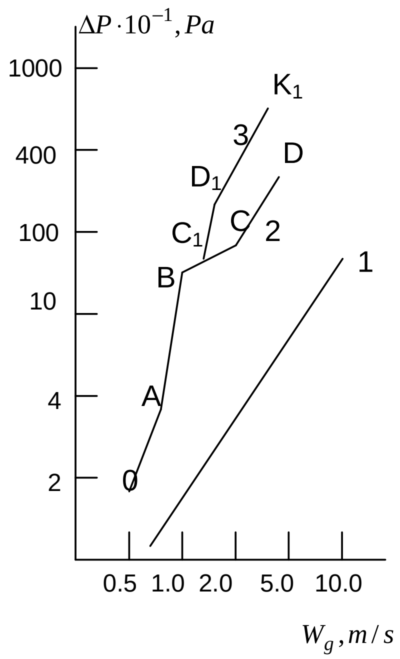
Thus, the gas-liquid layer will have qualitatively new structure [2, 5].

It can be explained only by occurrence of a new regime that is essentially different from others.

On Fig. 2 we can see the dependence of ΔP on W_g in the apparatus with plates with large and rather small apertures. The main interest represents the site D_1K_1, corresponding to the regime of secondary foaming at which the developed vortices interaction of phases exists, i.e. penetration of gas vortices through a surface between phases is reached. Thus the gas-liquid mixture represents "raging" foam.

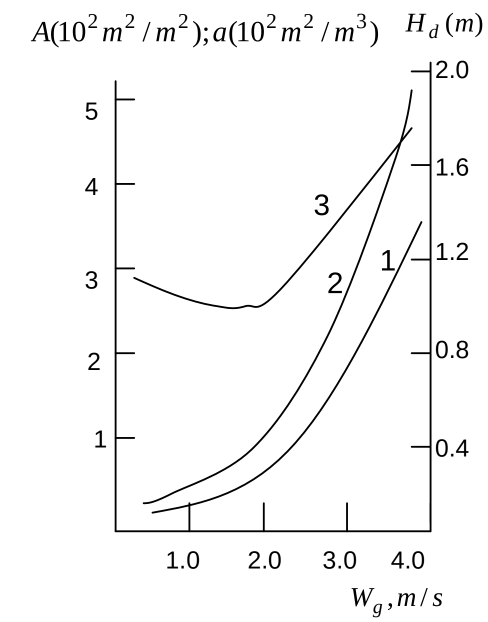


1-dry plate; 2,3-irrigated plate:2- $d_0 = 0.02m$;3- $d_0 = 0.06m$

Fig.2 Dependences of the pressure drop ΔP on gas velocity W_g

Advantages of the given regime concerning the power expenses for its realization are accurate obvious by comparison of dependences on Fig. 2 and 3. At increasing W_g from 2 to 4 m/s the growth of pressure drop is more than in two times, the growth of dynamic height of the gas-liquid layer is in 3.5 times, and growth of the gas-liquid contact surface is more than in 5 times. As it is clear visible the surface of gas-liquid contact per unit of the area of the perforated plate increased much more intensively than growth of the height of the gas-liquid layer and than the energy expenses. This phenomenon testifies to qualitative change of the layer structure. It is confirmed also by increase of the specific gas-liquid surface in 1.5 times with increasing gas velocity from 2 to 4 m/s.

The analysis of the known data [1, 3] shows, that the similar regime of interaction between phases was not observed by other investigators.



$S_0 = 0.2$ m^2/m^2, $L_0 = 5$ m^3/m^{2}h, $d_0 = 0.06$ m

Fig. 3 Dependences of dynamical height of the gas-liquid layer H_d (1), surface of phases contact per unit of the plate surface A(2) and surface of phases contact per unit of the column volume a (3)

Earlier the emulsion regime [3], which arises after an inversion point, has been described. However, it is observed at low velocities of gas (W_g <0.5 m/s) and this regime can not be considered as stable because the critical velocities of gas corresponding to the beginning of this regime, are close to the velocities corresponding to the choking of the column. Applying to the apparatuses with plates with large apertures, the regime of secondary foaming which is characterized by intensive growth of the surface of liquid-gas contact, comes also after inversion of phases, but has wide area of stable existence. Thus, occurrence of two stable foaming regimes with an intermediate unstable regime of the inversion of phases on the one plate can be qualified as the new phenomenon.

This phenomenon of secondary foaming opens new possibilities for carrying out heat and mass transfer apparatuses with high hydrodynamic efficiency (i.e., the relation between useful power for development of an inter-phase surface and a full expense of energy). This phenomenon is revealed on all plates with large apertures (at d_0> 0.03) in the investigated bounds of free section (S_0=0.1—0.5 m^2/m^2) and even at small density of an irrigation. Under increasing the density of liquid irrigation the phenomenon is shown even more well-defined.

For revealing the mechanism of secondary formation of foam and efficiency of columns with large apertures in plates the elementary interactions of phases have been studied at the gas flows through the liquid layer on plates with apertures with diameters 0.015, 0.03, 0.04, 0.06 and 0.09m. Under studying streaming with high velocity through a large aperture the toroidal vortices which crush the surface of gas-liquid contact have been observed [4].

Results of the experimental researches of the gas flowing both through the one aperture and the group of apertures have shown that nearby to apertures the profile of the gas concentration in liquid is identical to the profile of a dynamic pressure of the single-phase streams which is well described by the approximation.

$$\varphi/\varphi_m = 1 - 6k^2 + 8k^3 - 3k^4 , \quad (1)$$

where $k = 0.39\, x/x_{\varphi m/2}$; x is the horizontal coordinate with zero at the aperture axis; $x_{\varphi m/2}$ is the distance between the aperture axis and the point with $\varphi_m = 0.5$; φ_m is the gas concentration in the layer nearby the axis of aperture.

For a quantitative estimation of the critical diameter $d_{0,cr}$ of an aperture corresponding to the initial stage of the regime of secondary foaming we consider the equation of wave distribution over a liquid surface [1]. Movement of an interface of phases in case of its big curvature can be described as follows [2]

$$\frac{\partial^2\eta}{\partial t^2} + gh_0 \frac{\partial^2\eta}{\partial x^2} , \quad (2)$$

where η is the potential of velocity.

The liquid layer oscillates with certain frequency and period:

$$\eta(x,t) = T(t)\sin kx . \quad (3)$$

Substituting expression (3) in the equation (2), we obtain

$$\frac{\partial^2 T}{\partial t^2} - gh_0 k^2 T . \quad (4)$$

The solution of (4) reads

$$T = F \exp\left(kt\sqrt{gh_0}\right) + B \exp\left(-kt\sqrt{gh_0}\right). \quad (5)$$

It is follows from initial conditions that $F \neq 0$.

So, the amplitude of oscillations (3) grows, and movement of the interface of phases appears unstable. In reality, the harmonics, which length of waves became more than the critical size λ became unstable. This value is the control parameter for definition of the critical diameter of apertures on a plate for considered two-phase system: $d_{0,cr} \approx \lambda_{\min}$. It can be calculated as [5]

$$d_{0,cr} \approx \lambda_{\min} = 2\pi\sqrt{\frac{3\sigma}{\rho_l g}} , \quad (6)$$

where ρ_l is the liquid density, and σ is a superficial tension.

The calculations spent on this equation, have shown that for system of air-water at normal temperature we had the critical diameter $d_{0,cr} \approx$ 0.03 m. Therefore the rather steady bubbles are formatted at $d_0 < d_{0,cr}$, and the basic regularities of interaction of phases on a plate don't differ from hydrodynamics of plates with d_0 from 0.01 to 0.012 m.

At $d_0 > d_{0,cr}$ these regularities change both qualitatively and quantitatively (Fig. 1 and Fig. 4).

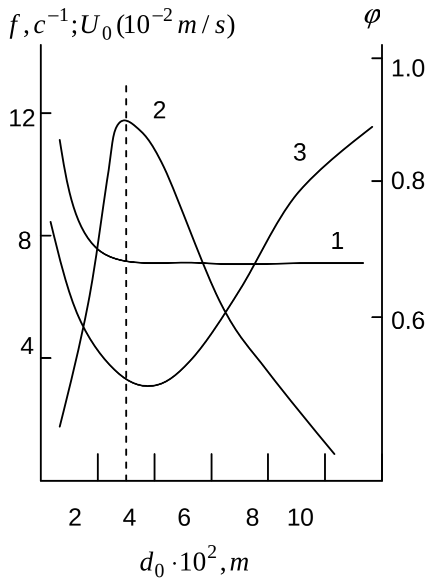


Fig. 4 Dependences of the frequency of bubbles formation f (1), the intensity of liquid downfall U_0 (2), and the gas phase concentration in the layer φ(3) on the diameter of aperture d_0

Critical velocity of gas W_{cr}, corresponding to the beginning of a regime of secondary foaming, can be defined from the relation

$$\frac{W_{cr}}{gS_0^2 d_{0,cr}} \frac{\rho_g}{\rho_l} = 5\left(\frac{d_{0,cr}}{d_0}\right)^2 \exp\left[-4\left(\frac{Q}{G}\right)^{0.25}\left(\frac{\rho_g}{\rho_l}\right)^{0.125}\right], \quad (7)$$

where ρ_g is the gas density, Q, G are mass velocities of a liquid and gas.

The experimental data have shown that at certain parities of height of the liquid layer on a plate and diameter of the apparatus the amplitude of oscillation of gas-liquid layer becomes maximal irrespective of the velocity of gas stream. The oscillation of layer on a plate occurs in a horizontal direction, and its amplitude has been sharply increased at coincidence of nearest points of extremes of parallel waves [2] with a wall of the column. Then the expression for the height of a layer can be written from some rearrangements as follows

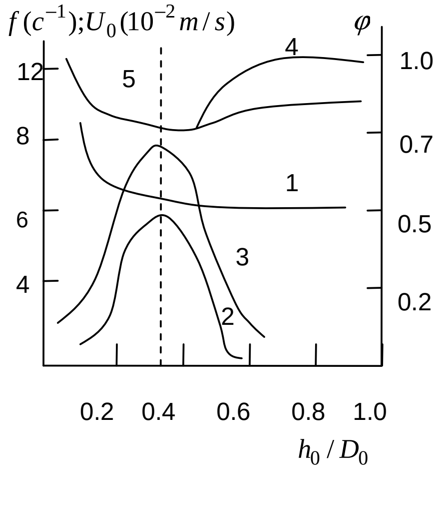
$$h_0 = gT^2 / 4\pi^2 . \quad (8)$$

The critical relation at which the gas-liquid layer on a plate will oscillate with the greatest amplitude can be evaluate as

$$h_0 / D_a = 1/\pi \approx 0.318 . \quad (9)$$

So, the relation (h_0 / D_a) is the control parameter of instability which characterizes influence of constructive parameters of the apparatus on occurrence of resonant oscillations of the gas-liquid layer on a plate.

Fig. 5 depicts the results of experimental investigations of the frequencies of bubbles formation, the intensity of a downfall of the liquid and concentration of gas phase in the layer nearby an axis of an aperture as functions of the relation h_0 / D_0



d_0: 1, 2, 4, 5- 0.06 m; 3- 0.15 m; W_g : 1, 4- 10 m/s; 3-8 m/s; 5-2 m/s

Fig. 5 Dependences of the frequency of bubbles formation f (1), the intensity of liquid downfall U_0 (2, 3), and the gas phase concentration in the layer (4, 5) on h_0 / D_0

Essential changes occur in behavior of the curves (Fig. 5) when the relation (9) is fulfilled. Only frequency decreases to this critical parameter, but further one slightly changes that testifies the stabilization of the hydrodynamic regime. Decrease of the pressure drop for the apparatus of the diameter 0.35 m (Fig. 1) can be explained by that at d_0=0.06 the resonant oscillation of the gas-liquid layer intensifies, and the intensive downfall of a liquid is reached too.

The described phenomenon should be considered at designing heat and mass transfer apparatuses with counter-flow plates. For maintenance lowest gas-liquid layers it is necessary to define the cross-section size of a cell of partitions at plates from relation (9). It may be important, for example, for foamy columns with special stabilizing devices of gas-liquid layers.

III. Discussion and Conclusion

So, the distinctive features of the phenomenon of the secondary foaming are: 1) its occurrence on counter-flow plates in formerly unknown bounds of constructive and regime parameters (after an unstable regime of inversion of phases); 2) stable existence both in a wide range of gas velocities through the column and the size of apertures in plates; 3) formation of high stable gas-liquid layer with qualitatively new hydrodynamic structure; 4) the simultaneous expiration of gas and a liquid through apertures, namely: a liquid flows as a pulsing stream, and a gas stream in the form of toroidal vortices with the same time phase; 5) high hydrodynamic efficiency. The distinctive peculiarities of the phenomenon of resonant oscillation of gas-liquid layer are: 1) its occurrence in counter-flow columns in the wide range of regime parameters; 2) the possibility of controlling both hydrodynamic and structural parameters, and, hence, the efficiency of heat and mass transfer process may be reached by means of change of the geometrical sizes of a cell of section.

These new regularities have formed a creation basis of high-intensive heat and mass transfer and gas purifying apparatuses, which advantages are: simplicity and reliability of construction, big capacity. The plates are offered, which do not become obstructed by deposits.

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