Simulation of the method of excitation of pulsations in a moving fluid flow

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Abstract. The article deals with an important issue of efficiency of using energy supplied into each of the elements of the Venturi-type pipe, i.e. the value of energy efficiency coefficient. The issue coverage requires conducting comparative studies of the specific surface area of bubbles in a gas-liquid system and the mass transfer coefficients in a pipe with a periodically changing cross-section and in a cylindrical pipe with other conditions being equal. The proposed method of excitation of pulsations in a moving fluid flow can be used for the processes of splitting droplets and bubbles in a continuous liquid phase, since this creates favorable conditions – significant amplitudes of pressure, speed and acceleration at a frequency of about dozens of Hertz.

1. Introduction

The article deals with an important issue of efficiency of using energy supplied into each of the elements of the Venturi-type pipe, i.e. the value of energy efficiency coefficient. The issue coverage requires conducting comparative studies of the specific surface area of bubbles in a gas-liquid system and the mass transfer coefficients in a pipe with a periodically changing cross-section and in a cylindrical pipe with other conditions being equal.

2. Results and Discussion

Several modes of two-phase flow in a horizontal channel that are characteristic of hydraulic resistance and heat exchange can be conventionally distinguished. This is a stratified flow that includes layered and wave flows, projectile and wave flows with jumpers, as well as flow modes that do not depend on the orientation of the channel – bubble and annular flows, including wavy-annular and dispersed-annular flows [1]. In an annular channel, flow modes are qualitatively consistent with the specified flow modes in the pipe. However, the channel's outer diameter is one of the determinant parameters for detecting the stratification conditions of a two-phase flow in an annular channel. Size of the annular gap affects the flow structure in a wavy-annular flow. Thus, reduction of the annular gap leads to the contact of the vertices of individual waves on the surface of liquid films at both walls of the channel with the formation of screw-like mutually overlapping liquid bridges. The distance, or pitch, between these bridges is about four outer diameters of the annular channel. It should be noted that the film of the channel's inner wall is thinner than that of the outer wall, and accordingly, the drying of the former is more speedy in a dispersed-annular flow. The analysis of literature and generalization of the results obtained on vapor-liquid flows of helium and nitrogen in the annular and round channels, as
well as investigation of the known maps of flow modes for two-phase flows of water and freon, have allowed proposing calculated relations for determining the conditions of transition to the flow modes characteristic of resistance and heat exchange [2-4]:

The cyclic frequency of pulsations of pressure, speed, and acceleration in this case is determined by the formula

$$\omega = \frac{2\pi}{T}. \quad (1)$$

The pressure distribution can be approximated with sufficient accuracy for engineering calculations using a one-dimensional model.

According to [1], the local resistance coefficient for the confuser is written as

$$\zeta_m = -0.0125 n_0^3 + 0.0224 n_0^3 - 0.00723 n_0^2 + 0.00444 n_0 - 0.00745 \left(\frac{\alpha}{2\pi}\right)^3 - 10 \alpha, \quad (2)$$

where $n_0 = (d/D)^2$ – degree of narrowing of the flow; $\alpha$ – angle $\alpha$ expressed in radians.

The coefficient of friction loss in the confuser is determined by the formula

$$\zeta_{f.c} = \lambda_1 \left(1 - n_0\right)^2 / 8\tan(\alpha/2), \quad (3)$$

where $\lambda_1$ – coefficient of hydraulic friction, which is calculated using the Altschul formula in a section with a diameter $D$:

$$\lambda_1 = 0.11 \left[(68/\text{Re}_D) + (\Delta/D)^{0.25}\right] \quad (4)$$

$\text{Re}_D = \frac{w_2 D \rho}{\mu}$ – Reynolds number, which is calculated from the cross section with a diameter $D$; $\rho$ – density of the liquid, kg/m$^3$; $\mu$ – coefficient of dynamic viscosity, PA*s; $\Delta$ – absolute roughness of the inner surface of the pipe, m.

The pressure loss in the confuser can be represented as [2]

$$\Delta p_\text{c} = (\zeta_m + \zeta_{f.c}) \left(\rho \frac{w_1^2}{2}\right). \quad (5)$$

The impulse completeness coefficient for the operating diffuser is represented in [3] by the formula

$$\varphi = 3.2 \left[\tan(\beta/2)/\left(\rho \frac{w_2}{2}\right)\right]^{0.25}, \quad (6)$$

The coefficient of resistance conditioned by expansion of the flow is represented as follows:

$$\zeta_{\text{exp}} = \varphi \left(1 - n_0\right)^2. \quad (7)$$

According to [4], the coefficient of friction loss in the diffuser is determined by the formula

$$\zeta_{f.d} = \lambda_{av}(1-n_0)^2/8\tan(\beta/2), \quad (8)$$

where $\lambda_{av}$ – coefficient of hydraulic friction calculated as the arithmetic mean: $\lambda_{av} = (\lambda_1 + \lambda_2)/2$; and the coefficient of hydraulic friction $\lambda_2$ is calculated using the Altschul formula in a section with a diameter $d$:

$$\lambda_2 = 0.11 \left[(68/\text{Re}_D) + (\Delta/D)^{0.25}\right], \quad (9)$$

where $\text{Re}_d = w_1 d \rho/\mu$ – Reynolds number calculated from the cross section with a diameter $d$.

The pressure loss in the diffuser is represented in [5] as

$$\Delta p_d = (\zeta_{f.d} + \zeta_{\text{exp}}) \left(\rho \frac{w_1^2}{2}\right). \quad (10)$$

Compression of the flow in the Venturi pipe necks can be ignored, which is confirmed by our finite element calculations.

Then the pressure loss in the narrow neck is determined by the formula

$$\Delta p_\text{n} = \lambda_2 \left(\frac{L_2}{d}\right) \left(\rho \frac{w_1^2}{2}\right), \quad (11)$$

and in the wide neck – by the formula

$$\Delta p_\text{d} = \lambda_1 \left(\frac{L_4}{d}\right) \left(\rho \frac{w_2^2}{2}\right). \quad (12)$$

Total irreversible pressure loss in a single Venturi-type element of length $L$ is determined by the sum of losses

$$\Delta p = \Delta p_\text{c} + \Delta p_\text{d} + \Delta p_\text{n} + \Delta p_0. \quad (13)$$

Assuming the flow being smoothly changing everywhere, it is not difficult to obtain formulas for calculating the pressures in sections 1-4 from the Bernoulli equation (Figure 1):

$$p_1 = P_0 + \left(\rho \frac{w_1^2}{2}\right) - \Delta p_\text{c}; \quad (14)$$

$$p_2 = p_1 - \Delta p_\text{d}; \quad (15)$$

$$p_3 = p_2 + \left(\rho \frac{w_1^2}{2}\right) - \Delta p_\text{n}; \quad (16)$$

$$p_4 = p_3 - \Delta p_0. \quad (17)$$
Graphs of the distribution of speeds, accelerations, and pressures along the length of a Venturi-type element, given to the x coordinate, are shown in Figure 2.
Figure 2. Theoretical distribution of speeds $w$, accelerations $a$ and pressures $p$ along the length $x$ of the confuser-diffuser element (calculated parameters: $d = 10$ mm; $D = 20$ mm; $L_1 = 15$ mm; $L_2 = L_4 = 10$ mm; $L_3 = 50$ mm; $\alpha = 36^\circ$; $\beta = 11.5^\circ$; $Q = 7.8 \times 10^{-4}$ m$^3$/s)

Special attention should be paid to the fact that acceleration and deceleration maxima are located near the narrowest part of the pipe – the neck with a diameter $d$. Particles of the deformable dispersed phase, approaching the neck, start to accelerate, especially near the axis of the pipe, stretching in the axial direction. At the same time, they undergo a significant drop in hydrostatic pressure. After passing the neck, the liquid begins to brake sharply, while the pressure is restored almost to the initial value. The wall layers of the liquid are greatly affected by huge shear stresses due to large transverse velocity gradients at the neck walls. Combination of these factors can serve as a powerful means of deforming and splitting dispersed inclusions, as well as contribute to wave formation on their surface and improvement of internal mixing and, in general, accelerate mass transfer processes.

In addition, a drop in the pressure in the neck to the value of saturated vapors can lead to cavitation and associated effects [6, 7]. As for solid particles that have a density different from a liquid, their constant acceleration and deceleration should also enhance mass transfer. When processing capillary-porous particles, the acceleration of mass transfer inside the particle can be facilitated by pressure pulsation [8, 9], and outside – by periodic pulsation renewal of liquid near the surface of the particle [10].

Figure 3 shows the pressure distribution in a pipe with a periodically changing cross-section consisting of 10 consecutive elements of the Venturi-type pipe, which has been calculated using the formulas (14)–(17), taking into account the ratios (9)–(12).

The calculated parameters are shown in the caption to Figure 2. The results obtained have been tested experimentally on a glass model of such a pipe with a periodically changing cross-section. The flow rate of the liquid in the pipe varied in the range $(1.16–2.98) \times 10^{-4}$ m$^3$/s, the flow mode being turbulent ($Re_d > 9500$).
The results of measurements and calculations have been generalized by a dependency of the form
\[ \Delta p_0 = CQ^2, \]  
where \( \Delta p_0 = 10 \Delta p \) – pressure loss in the pipe consisting of 10 consecutive elements of the Venturi type; \( C \) – pressure loss coefficient.

3. Experiment

According to experimental data, the coefficient \( C \) makes \( 2.61 \cdot 10^{11} \) kg\( \cdot \)m\(^{-7} \), while the calculation using formulas (9)–(13) at \( Q = 2.8 \cdot 10^{-4} \) m\(^3\)/s gives a theoretical value of the coefficient \( C \) equal to \( 1.69 \cdot 10^{11} \) kg\( \cdot \)m\(^{-7} \), which is 1.54 times less than the experimental value. This discrepancy may be explained by the error in manufacturing of a complex-shaped glass tube, deviations of its linear and angular dimensions from the design (when the diameter of the neck deviates from the nominal by only 8%, the resistance of the pipe increases by 1.52 times); the error in measuring pressure and flow, as well as the fact that the coefficient of completeness of the impulse of the diffuser is calculated on the basis of the rectangular speed profile in a narrow section.

At the same time, the nature of the experimental dependence (19) coincides with the nature of the theoretical one, which allows recommending the proposed calculation method for engineering calculations of a pipe with a periodically changing cross-section.

It should be noted that for the cylindrical pipe with the diameter of 10 mm and the length of \( 10L = 0.85 \) m at \( Q = 2.8 \cdot 10^{-4} \) m\(^3\)/s, the theoretical value of the coefficient \( C \) has made \( 1.76 \cdot 10^{11} \) kg\( \cdot \)m\(^{-7} \), which is 4.1% higher than the theoretical value of the coefficient for a pipe with a periodically changing cross-section. This is due to the fact that, firstly, its profile provides a continuous flow of liquid, and, secondly, in some areas, the flow rate of the liquid is lower. Thus, despite the complex shape of the pipe with a periodically changing cross-section, the overall energy loss in it is somewhat lower.

The theoretical frequency of pulsations according to formula (9) at \( Q = 2.8 \cdot 10^{-4} \) m\(^3\)/s for the pipe of the considered shape is 130 rad/s. Unfortunately, the experimental verification of this ratio is difficult due to the need to move the pressure sensor inside the pipe along with the flow.
4. Conclusion

The proposed method of excitation of pulsations in a moving fluid flow can be used for the processes of splitting droplets and bubbles in a continuous liquid phase, since this creates favorable conditions – significant amplitudes of pressure, speed and acceleration at a frequency of about dozens of Hertz.

Combination of these factors can serve as a powerful means of deforming and splitting dispersed inclusions, as well as contribute to wave formation on their surface and improvement of internal mixing and, in general, accelerate mass transfer processes. These factors can also help speed up the mass transfer process when processing solid impervious and capillary-porous particles.

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