Hydrodynamic Features of Gas-Liquid Flow Movement in a Separation Device Plane Channel with an Oscillating Wall

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Abstract. In this paper, the movement of a gas-fluid flow in a plane channel with an oscillating wall was investigated. The aim of the research is to increase the efficiency of separation equipment by imposing the vibration impact on a gas-liquid flow. This purpose was achieved by applying the phenomenon of selective coagulation of a dropping liquid. The novelty of the proposed approach concerns creating the mathematical model for determination of analytical dependences between the efficiency of the hydromechanical process and initial parameters of the separation device. As a result, quantitatively and qualitatively sufficient approximations for the scalar pressure and vector velocity fields were obtained with a permissible relative error in comparison with the results of numerical simulation. The presence of biharmonic fluctuation of particles was proved; besides, related dependencies for the calculation of vibration characteristics were obtained. Additionally, the paper presents the dependencies for identifying a range of thickness for a near-wall area. The system of dimensionless criteria was proposed for determining flow modes and relative trajectories of liquid droplets in a gas-fluid flow. The numerical simulation approach and related methodology of engineering calculations were proposed on the example of a plane channel of the separation device. Finally, the distance between adjacent zones of the pressure minimum was determined. As a result, it was found that this distance is equal to the wavelength of the vibrating impact to the flow that is an initial justification of further coagulation process of liquid droplets in a gas-liquid flow in a separation device.
***Keywords*:** vibration impact, local zone, pressure, dropping liquid, velocity field, trajectory of a particle.
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Caracteristicile hidrodinamice ale mișcării unui flux gaz-lichid într-un canal plat al unui dispozitiv de separare cu un perete oscilant

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Rezumat. Se investighează mișcarea fluxului de gaz-lichid într-un canal plat cu un perete oscilant. Scopul acestei lucrări constă în sporirea efiicienței echipamentului de separare prin impunerea unui efect de vibrație asupra fluxului de gaz-lichid. Acest obiectiv este realizat prin utilizarea coagulării selective a fluidului picăturilor. Noutatea științifică constă în elaborarea modelui matematic pentru determinarea funcțiilor analitice a eficienței procesului hidromecanic a dispozitivului de separare. Estimarea directă a parametrilor sistemului "perete oscilant - amestec gaz-lichid" cu semnificații non-lineare este imposibilă. În lucrare se examinează un caz particular de mișcare a fluxului gaz-lichid, caracterizat de trei criterii non-dimensionale. S-au obținut relații analitice care reflectă calitativ și cantitativ câmpul de presiune scalară și câmpul vectorului de viteză cu o eroare admisibilă în comparație cu rezultatele simulării numerice. S-a confirmată prezența fluctuațiilor biarmonice ale particulelor ca urmare a efectului de vibrație și s-au obținut realțiile analitice pentru calcularea caracteristicilor corespunzătoare și relațiile pentru calcularea grosimii stratului de lichid din zona peretelui. S-a propus un sistem de criterii non-dimensionale pentru a determina regimurile de curgere, formule de caclul ale traiectoriilor relative ale lichidului de picurare în fluxul gaz-lichid, metodă numerică de simulare și o metodologie adecvată a calculului parametrilor hidrodinamici ai debitului de gaz-lichid într-un canal plat al dispozitivului de separare. S-a determinat distanța dintre zonele de presiune minimă locală, constatând că această distanță este egală cu lungimea de undă a efectului de vibrație al peretelui pe flux, care ete confirmarea derulării ulteriore a procesului de coagulare selectivă a lichidului de picurare în canalul plat al dispozitivului de separare.
Cuvinte-cheie: vibrații, zonă locală, presiune, lichid din picături, câmp de viteză, traiectorie de particule.

Гидродинамические особенности движения газожидкостного потока в плоском канале сепарационного устройства с колеблющейся стенкой

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Аннотация. В работе исследовано движение газожидкостного потока в плоском канале с колеблющейся стенкой. Целью данной работы является повышение эффективности сепарационного оборудования путём наложения вибрационного воздействия на газожидкостный поток. Эта цель достигается за счёт применения явления избирательной коагуляции капельной жидкости. Научной новизной предложенного подхода является создание математической модели для оценивания аналитических зависимостей между эффективностью гидромеханического процесса и исходными параметрами сепарационного устройства. Вследствие невозможности непосредственного оценивания параметров гидромеханической системы «колеблющаяся стенка – газожидкостная смесь» с имеющимися существенными нелинейностями в данной работе рассмотрен частный случай движения газожидкостного потока, характеризуемый соотношением трёх предложенных безразмерных критериев. В результате получены аналитические зависимости, качественно и количественно отражающие соответствующие аппроксимации для скалярного поля давления и векторного поля скорости с допустимой погрешностью по сравнению с результатами численного моделирования. Также доказано наличие бигармонических флуктуаций частиц в результате вибрационного воздействия на поток, а также получены аналитические зависимости для расчёта соответствующих характеристик. Дополнительно представлены соотношения для определения расчётного диапазона толщины пристеночного слоя. Введена система безразмерных критериев для определения режимов движения потока, а также форм и геометрических размеров относительных траекторий капельной жидкости в газожидкостном потоке. Предложен способ численного моделирования, а также соответствующая методология реализации инженерного расчёта гидродинамических параметров газожидкостного потока в плоском канале сепарационного устройства. Также определено расстояние между зонами локального минимума давления. В результате доказано, что это расстояние равно длине волны вибрационного воздействия стенки на поток, что является начальным подтверждением последующего процесса избирательной коагуляции капельной жидкости в газожидкостном потоке в плоском канале сепарационного устройства.

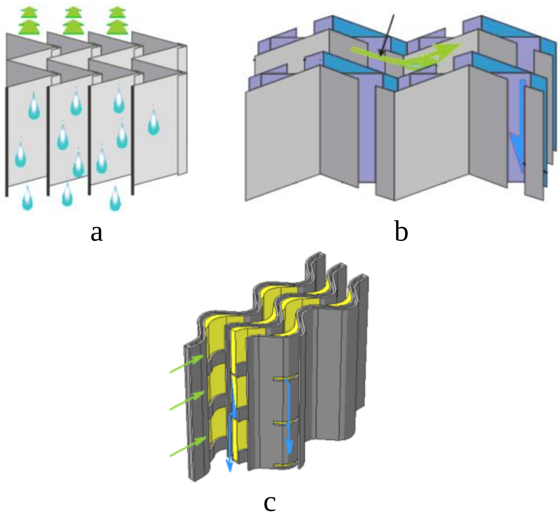
Ключевые слова: вибрации, локальная зона, давление, капельная жидкость, поле скорости, траектория частицы.

INTRODUCTION

The separation processes for multicomponent heterogeneous systems are among the most complex in the physical and mathematical description while they are widely used in chemical, petroleum, oil and gas industries. At the same time, high-technological equipment must have the highest indicators of energy efficiency and reliability. The problem of avoiding emergencies in the existing compressor equipment, as well as increasing wear of operating parts of assemblies is an urgent problem in chemical and petroleum engineering, pump and compressor industries.

The first attempts of implementation of inertial and filtering separations and designing the corresponding separation devices were made by Sumy State University in 2003. In 2007, SulzerAG (Mellachevron®) and Koch-Glitsch (FLEXICHEVRON™) proposed their technical solutions for designing double louvres, traps and drainage channels, which were introduced into the mass production in 2013.

The design schemes described above are presented in Fig. 1.



a – Mellachevron® (Sulzer);
b – FLEXICHEVRON™ (Koch-Glitsch);
c – Sumy State Univeristy.

Fig. 1. The design schemes of the separation equipment louver packages.

Based on the analysis of possible ways to improve the existing separation equipment, the brand-new technology for vibration and inertial separation of gas-liquid flows is proposed and presented in the paper “Appliance of inertial gas-dynamic separation of gas dispersion flaws in the curvilinear convergent-divergent channels for compressor equipment reliability improvement".

However, the existing mathematical models does not cover all the aspects for describing the physical features of hydromechanical, heat and mass transfer operating processes in the related separation and purification equipment. Moreover, all the recent researches are based on complicated nonlinear models that cannot be solved directly. In this regard, there is a wide variety of computational methods of research and numerical simulation approaches. However, they do not allow predicting the behavior of a comprehensive hydromechanical system in a wide range of its operating parameters.

Due to the abovementioned, the row of researches has been carried out for providing quantitatively and qualitatively approximation of the proposed models and related calculating approaches to the physical features of the movement of gas-liquid flows in channels of separation equipment. The recent research works are discovered below.

LITERATURE REVIEW

The research work "Management of Energy Flows in Low-temperature Separation Units" (authors: Trishyn F.A., Trach O.R., Orlovskaya Yu.V.) is particularly aimed at investigating the impact of ultrasound on the separation process. As a result, the importance of using thermal energy in separation units is proved, as well as the overall energy efficiency estimation technique was proposed based on the hypothesis of direct and reverse energy flows. The methodology of numerical simulation of the process of incineration of a mechanical mixture is presented in the article "Combustion of Solid Fuel in a Vortex Furnace with Counter-swirling Flows" (authors: Redko A.A., Redko I.A., Redko A.F.). As a result, the swirling flow rate was estimated for ensuring the efficiency of separation process. The problems of design, evaluation and application of the swirl technologies for separation of liquid purification systems are discussed in the articles [1, 2]. However, these approaches do not allow determining analytical dependences between flow parameters and initial conditions of the hydromechanical system. A method for expanding a range of separation elements is presented in the previous work "Solving the stationary hydroaeroelasticity problem for dynamic deflection elements of separation devices", where the separation process is realized using inertial forces acting to particles. Such approach allows solving the stationary problem of hydroaeroelasticity for self-adjustable deformable deflection elements of the separation device. However, this method was not being still realized practically, and should be proved in further research.

The research works [3–5] deals with the saturation of a filtering liquid with a gas both in sequential and simultaneous feedings to the apparatus of chemical industry. As a result, the gas consumption factor is significantly reduced. The research work "Modelling of liquid's distribution and migration in the fibrous filter layer in the process of inertial-filtering separation" concerns determining the saturation conditions for the filter layer, as well as modeling distribution of the velocity and pressure under the conditions for the movement of a liquid in a filter layer under the gravitational force. This allows clarifying the processes of distribution and migration of liquid droplets of gas-liquid mixture in the fibrous filter layer during the inertial-filtering separation process in separation equipment. However, the mentioned materials do not consider the impact of oscillations on the rising filtering efficiency.

The mathematical model as the system of differential equations of relative displacements of particles is investigated in the article [6] for the oscillating cylindrical surface. The results of experimental data allowed obtaining the regression equations for determining the separation quality, as well as for designing the response surface. The disadvantage of this work is using only kinematic approach despite the comprehensiveness of the stated problem.

The methodology for selection and comprehensive evaluation of separators for the gas and oil industries is proposed in the papers [7, 8]. The database of weight and size parameters of separators allowed obtaining dependences between the type of apparatus, its operating pressure and consumption. The model of crossed movement and gas-liquid flow interaction with captured liquid film in the inertial-filtering separation channels is proposed in the article "The model of crossed movement and gas-liquid flow interaction with captured liquid film in the inertial-filtering separation channels". As a result, the physical model of a gas-liquid flow is proposed, as well as the equations for determination of the main parameters of captured liquid film and gas-liquid flow interactions are obtained. But these researches have no reliable mathematical models to predict operating parameters of the separation process under the arbitrary operating conditions.

However, the research papers [9, 10] is aimed at developing the predictive model for simulating reactive micro-separation processes, as well as designing separation equipment, as well as a brand-new method of gas purification is presented in the article “Modeling and design of inertial-filtering gas separators-condensers for compressor units of oil and gas industry” using a method of condensation separation. Additionally, the mentioned work presents experimental results of the research. As a result, the models of separation process in the inertial-filtering separators-condensers are proposed for compressor plants in oil and gas industries. However, these models are also limited by numerical experiments only and need to be extended by creating reliable mathematical models.

Another way for effective oil-water separation is proposed in the research work [11] using magnetic superhydrophobic materials. Authors assert this approach as a potentially effective way for oil-water separation. In addition, the recent trends in liquid-gas and solid-gas separators are described in the work [12] for industrial equipment in the field of chemical engineering. The designs of separators and its operational parameters are presented, as well as methods of numerical simulation are proposed. In another way, the work [13] is focused on up-to-date technologies and related technological processes of energy recovery and water recycling. As a result, the recommendations are provided regarding proper design of technological equipment in specific situations. Additionally, the work [14] deals with optimal selection of the separation and purification equipment and proper using theirs operating processes. Better understandings of separation and purification processes, as well as advanced methods are proposed for achieving the overall techno-economic feasibility and commercial success. It should be noted that the researches [11–14] have a limited scope, mainly in water recycling.

It should be noted, that special interest of scientists is concerned to methods of numerical implementation of the developed models. Particularly, the approach of prediction for multi-grade processes in chemical engineering is presented in the paper [15] using just-in-time latent variable modeling. The article [16] is aimed at developing the scientific approach of using artificial intelligent systems for solving applied problems in the field of mechanical and chemical engineering. Particularly, the design schemes for direct and inverse mathematical modeling of hydromechanical processes are proposed.

Moreover, the approach for solving an interdisciplinary problem of hydroaeroelastic interaction of gas-liquid mixtures with deformable structural elements of the separation equipment is proposed based on the comprehensive implementation of artificial neural networks with the finite element method of numerical simulation. Another approach, which is proposed in the paper [17], deals with computer aided process planning based on classification methods and related systems. As a result, a new method of selective and dynamic classifications is proposed and described. However, the numerical approaches proposed in the papers [15–17] concern highly complicated methods for practical purposes.

Due to abovementioned, the research methodology presented below attempts to generalize the recent approaches retaining as an advantage the comparative simplicity and clarity of the proposed approach.

The aim of the research is increasing the efficiency of separation equipment by imposing the vibration impact on a gas-liquid flow. This purpose is achieved by applying the phenomenon of selective coagulation of dropping liquid by solving the following objectives: creating the mathematical model of the hydromechanical system “oscillating wall – gas-liquid flow”; identification of the dependences for a thickness of the near-wall area; evaluation of zones for pressure minimum; justification of the phenomenon for coagulation process of liquid droplets.

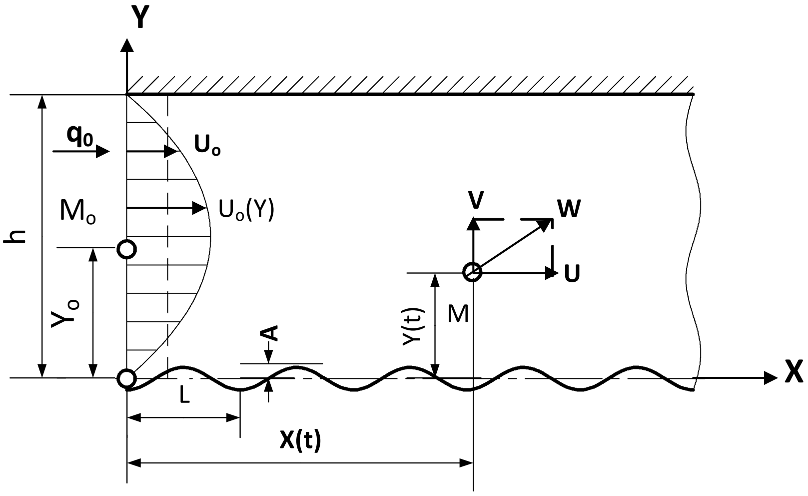
The scientific novelty of the proposed approach in comparison with the abovementioned works concerns creating the mathematical model able to evaluate the analytical dependences between the efficiency of the separation process and initial parameters of the separation device. Thereby, a thickness of the near-wall area is determined, trajectories of particles are built, and local zones of minimal pressure are identified.

The practical significance of the research concerns creating the methodology for designing separation devices with deformable dynamic elements (i. e. louvers and traps of the drainage channels).

I. METHODS OF RESEARCH

The movement of a gas-fluid flow in a plane semi-infinite channel between two parallel walls is considered. One of the walls is rigid, the second one is monoharmonically oscillating with the amplitude of vibration velocity a (m/s), angular frequency ω_0 (rad/s) and wave's length $L = 2\pi/\lambda$ (m), where λ – wave's parameter (m^{-1}). All the forces of non-hydrodynamic nature in a gas-liquid flow are considered absent or their effect on the motion of fluid droplets is quite negligible.

The design scheme is presented in Fig. 2.



$A = a/\omega_0$ – amplitude of the oscillations (m);
M_0 – initial position of a particle; u, v – components of the total velocity w (m/s).
Fig. 2. The design scheme.

In the research work [1] is shown that the streamline in such channel is determined using the following system of the nonlinear and nonstationary parametric equations with respect by the time t (s) and coordinates x, y (m) of the investigated particle for gas-liquid flow:

$$\begin{cases} \dfrac{dx}{dt} = \dfrac{6y}{h^3}(h-y)\left[q_0 + \dfrac{a}{\lambda}(1-\cos\lambda x)\sin\omega_0 t\right]; \\ \dfrac{dy}{dt} = \dfrac{a}{h^3}(h-y)^2(2y+h)\sin\lambda x \sin\omega_0 t, \end{cases} \qquad (1)$$

where; h – channel width (m); q_0 – specific flow rate (m^2/s):

$$q_0 = \int_0^h u_0 dy. \qquad (2)$$

In this equation inlet velocity u_0 (m/s) depends on the vertical coordinate y [18]:

$$u_0 = \frac{6q_0}{h^3} y(h-y). \qquad (3)$$

The system (1) is nonlinear and cannot be solved directly. Therefore, a partial example is needed to be considered for obtaining the sufficient approximation of the analytical solution with a qualitatively permissible relative error in comparison with the results of numerical simulation. Practically valuable example concerns the case when the flow rate q_0 dominates the amplitude $\Delta q_a = 2a/\lambda$ of the vibration flow rate $\Delta q = a/\lambda\cdot(1 - \cos\lambda x)\sin\omega_0 t$ as a result of influence of an oscillating wall to a gas-liquid flow.

Due to the abovementioned, the following dimensionless criterion should be added as the ratio of the amplitude value of the additional flow rate Δq_a to the specific flow rate q_0:

$$Cr_1 = \frac{\Delta q_a}{q_0} = \frac{2a}{\lambda q_0} = \frac{2}{\lambda h}\frac{a}{\bar{u}_0}, \qquad (4)$$

where $\bar{u}_0 = q_0/h$ is the average inlet velocity as a ratio of a flow rate q_0 and height h of the separation channel (m/s).

In the case of $Cr_1 << 1$, the system (1) takes the following simplified form:

$$\begin{cases} \dfrac{dx}{dt} = \dfrac{6y}{h^3}(h-y)q_0; \\ \dfrac{dy}{dt} = \dfrac{a}{h^3}(h-y)^2(2y+h)\sin\lambda x \sin\omega_0 t. \end{cases} \qquad (5)$$

Since the effect of the oscillating wall on a flow prevails in a close area $y/h << 1$, the last system can be simplified using a series expansion retaining the first order terms:

$$\begin{cases} \dfrac{dx}{dt} = \dfrac{6\kappa_1}{h} q_0; \\ \dfrac{dy}{dt} = \kappa_2 a \sin \lambda x \sin \omega_0 t, \end{cases} \quad (6)$$

where dimensionless κ_1, κ_2 take the following forms:

$$\kappa_1 = \frac{y_0}{h}\left(1 - \frac{y_0}{h}\right); \; \kappa_2 = \left(1 - \frac{y_0}{h}\right)^2 \left(1 + \frac{2y_0}{h}\right), \quad (7)$$

and $y_0 = y(0)$ is the initial coordinate as an initial height of the particle.

Solving the system (6) for initial conditions $x(0) = 0$ and $y(0) = y_0$ allows obtaining the analytical solution for velocity components of a gas-liquid flow:

$$\begin{cases} x(t) = u_0 t; \\ y(t) = y_0 + \dfrac{1}{2}\kappa_2 a \left(\dfrac{\sin \omega_1 t}{\omega_1} - \dfrac{\sin \omega_2 t}{\omega_2} \right), \end{cases} \quad (8)$$

where the following frequencies are introduced:

$$\omega_1 = \omega_0 - \lambda u_0; \;\; \omega_2 = \omega_0 + \lambda u_0. \quad (9)$$

Thus, the solution (8) indicates the presence of biharmonic fluctuation of particles with frequencies $\omega_{2,1} = \omega_0 \pm \lambda u_0$ and, respectively, periods $T_{2,1} = 2\pi/(\omega_0 \pm \lambda u_0)$.

The following criterion

$$Cr_2 = \lambda u_0 / \omega_0 \quad (10)$$

allows considering two different cases. For small wavelengths ($Cr_2 >> 1$), the decomposition of the right side of the equation (8) into the Taylor series with respect to the frequency ω_0 with the first order accuracy allows obtaining the following approximation:

$$\begin{cases} x(t) = u_0 t; \\ y(t) = y_0 - \dfrac{\kappa_2 a}{\lambda u_0} \sin \lambda u_0 t \cos \omega_0 t. \end{cases} \quad (11)$$

Otherwise, when $Cr_2 << 1$ (the case of relatively long wavelengths) it can be founded:

$$\begin{cases} x(t) = u_0 t; \\ y(t) = y_0 - \dfrac{\kappa_2 a}{\omega_0} \sin \lambda u_0 t \cos \omega_0 t. \end{cases} \quad (12)$$

II. RESULTS AND DISCUSSION

1. Thickness of the near-wall area

The analysis of the abovementioned formulas allows resuming that the particles reach the oscillating wall in the case when the initial coordinate y_0 does not exceed its limiting value y_0^b. Analytically, introduction the dimensionless parameter $\kappa_3 = a/(\omega_0 h)$ allows obtaining the following dependences for determining a range of the near-wall area thickness:

$$\begin{aligned} y_{0\,\min}^{b} &= \kappa_3 h \left(1 - 3\kappa_3^2\right); \\ y_{0\,\max}^{b} &= 0{,}29 h \sqrt{Cr_1}. \end{aligned} \quad (13)$$

2. Trajectories of particles

The trajectories of particles can be described by the following equation:

$$y(x) = y_0 + \frac{1}{2}\kappa_2 a \left(\frac{\sin \lambda_1 x}{\lambda_1} - \frac{\sin \lambda_2 x}{\lambda_2} \right), \quad (14)$$

where the wave parameters are introduced:

$$\lambda_{1,2} = \lambda \mp \frac{\omega_0}{u_0} = \left(1 \mp \frac{1}{Cr_2}\right)\lambda. \quad (15)$$

Thus, in the general case, the fluid particles carry out biharmonic oscillations with wavelengths $L_{1,2} = 2\pi/\lambda_{1,2}$, which differ from the natural wavelength $L = 2\pi/\lambda$ of the oscillating wall.

More precise determination of trajectories can be realized for the relative coordinates

$$\begin{aligned} \xi(t) &= \frac{\lambda h \omega_0}{6\kappa_1 a}\left[x(t) - u_0 t\right]; \\ \eta(t) &= \frac{2\lambda u_0}{\kappa_2 a}\left[y(t) - y_0\right] \end{aligned} \quad (16)$$

using the small perturbation method [19]. The relative trajectories are ellipses.

3. Local zones of minimal pressure

To determine the local zones of minimal pressure in a gas-liquid flow, the investigation of the pressure field as a function of the coordinates x, y and time t on the extremum is realized using methods of mathematical analysis.

The pressure function obtained in the research paper [1] has the following simplified analytical form:

$$\begin{aligned} p(x,y,t) = p_0 - \frac{6\mu a}{h^3}\Big[&(1 + Cr_3)\frac{2x}{\lambda} - \\ &- y(h - y) + \frac{2}{\lambda^2} \Big] \sin \lambda x \sin \omega_0 t, \end{aligned} \quad (17)$$

where the dimensionless parameter

$$Cr_3 = q_0\lambda / a. \tag{18}$$

For the case Cr_3 << 1 (insignificant specific flow rates of the fluid q_0 and relatively long wavelength $L = 2\pi / \lambda$ with relatively high value of the vibration velocity a), the pressure function has the following points of zero pressure gradient:

$$\begin{cases} x_n = \dfrac{1}{\lambda}\left(\arccos\dfrac{1}{1+\lambda^2 h^2/8} + 2\pi n\right), (n \in Z); \\ y_n = h/2. \end{cases} \tag{19}$$

Using the Tailor series allows obtaining the simplified dependence for coordinates x_n:

$$x_n = \frac{h}{2} - \frac{5}{192}\lambda^2 h^3 + \frac{2\pi n}{\lambda}. \tag{20}$$

This proves that the zones of the local minimum of pressure are shifted relative to the wave loops. Moreover, the distance between the next zones $(x_{n+1} - x_n)$ is equal to the wavelength $L = 2\pi/\lambda$.

This fact, as well as the periodic element $\sin\omega_0 t$ indicates that the vibration impact on the flow can be carrying out by the different ways. In the case of small wavelengths, when $2\pi/(\lambda d) > 1$ (d – diameter of liquid droplets), particles conversely move between the next zones of pressure minimum contributing to the discontinuity of droplets larger than the wavelength.

Otherwise, it leads to fluctuations of the liquid droplets within adjacent zones of the local pressure minimum. This case leads to the coagulation of droplets with a diameter d smaller than the wavelength L.

Moreover, the given cases allow proposing the application of the effect of selective separation by acting on a flow through vibrations, which are the superposition of two waves of different lengths L_I and L_{II} ($L_I < L_{II}$) shifted by the phase. In this case to the process of coagulation of liquid droplets can be realized with diameters in a range $[L_I, L_{II}]$.

4. Numerical simulation results

The system of nonlinear differential equations (1) describing the liquid flow in a plane channel with an oscillating wall cannot be solved directly using any analytical approaches. However, it can be solved numerically, particularly by the Runge–Kutta method. In this case, the row-vector of coordinates is introduced:

$$\{Y(t)\} = \begin{Bmatrix} Y_1 \\ Y_2 \end{Bmatrix} = \begin{Bmatrix} x(t) \\ y(t) \end{Bmatrix}, \tag{21}$$

with its initial value $\{Y\}_0 = \{Y(0)\} = \{0; y_0\}^T$, as well as the row-vector of partial derivatives is created:

$$D = \begin{Bmatrix} \dfrac{6Y_2}{h^2}\left(1 - \dfrac{Y_2}{h}\right)\left[q_0 + \dfrac{a\varphi}{\lambda}\left(1 - \cos\lambda Y_1\right)\right] \\ \left(1 - \dfrac{Y_2}{h}\right)^2\left(1 + \dfrac{2Y_2}{h}\right)a\varphi\sin\lambda Y_1 \end{Bmatrix}, \tag{22}$$

where $\varphi(t) = \sin\omega t$ is a time function.

The field of flow velocity can be presented in a complex plane with the following real and imagine parts (components of the vector flow velocity):

$$\begin{aligned} u &= \frac{6y}{h^2}\left(1 - \frac{y}{h}\right)\left[q_0 + \frac{a\varphi}{\lambda}\left(1 - \cos\lambda x\right)\right]; \\ v &= \left(1 - \frac{y}{h}\right)^2\left(1 + \frac{2y}{h}\right)a\varphi\sin\lambda x. \end{aligned} \tag{23}$$

As an example, the fluid flow in a plane channel is considered with the following parameters: channel height $h = 0.1$ m, initial velocity $u_0^{in} = 0.1$ m/s, dynamic viscosity of the environment $\mu = 1\cdot10^{-3}$ Pa·s, amplitude of the vibration deflections $A = 1\cdot10^{-3}$ m, frequency $f = 50$ Hz, wavelength $L = 5\cdot10^{-3}$ m.

As a result, the following parameters are obtained: specific flow rate $q_0 = 0.01$ m/s, wave parameters: $\lambda = 1257$ m^{-1}, $\omega_0 = 314$ rad/s; amplitude of the vibration velocity $a = 0.31$ m/s. The dimensionless criteria: $Cr_1 = 0.05$, $Cr_2 = 0.6$. A near-wall area is in a range $(1.0–6.5)\cdot10^{-3}$ m.

For the initial coordinate $y_0 = 2\cdot10^{-3}$ m, the following dimensionless coefficients can be calculated: $\kappa_1 = 0.02$, $\kappa_2 = 0.99$.

Initial velocity $u_0 = 0.01$ m/s. Wave parameters: $|\lambda_1| = 2.5\cdot10^3$ m^{-1}, $\lambda_2 = 2.8\cdot10^4$ m^{-1}.

As a result of numerical simulation using related computer-aided design software [20], a complex velocity field can be obtained.

Additionally, the results of numerical simulation are presented in Fig. 3 as streamlines of gas-liquid flow near the oscillating wall of the plane channel.

The figure 3 clearly shows a decrease of vibration amplitudes for particles in the gas-liquid flow distanced from the oscillating wall. Additionally, frequencies of this secondary process are also reduced. Moreover, mechanical beats are observed in the near-wall area due the imposition of two oscillations with similar frequencies. The same effect was proved experimentally [21].

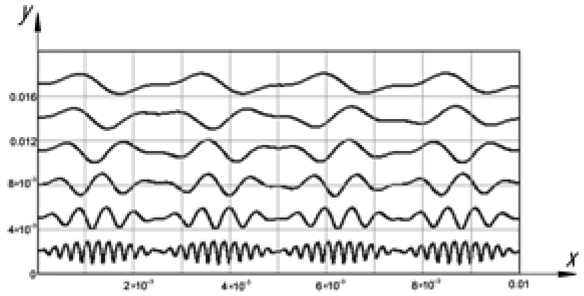


Fig. 3. Streamlines of gas-liquid flow.

The results of numerical calculations shown in Fig. 3 correspond to the analytical data with sufficient accuracy for practical purposes, even for more distant particles from the moving wall.

III. CONCLUSIONS

Thus, the hydrodynamics of the gas-liquid flow in a semi-infinite plane channel with an oscillating wall is considered. The analytical expressions for the fields of velocity and pressure are obtained. Streamlines of gas-liquid flow are determined analytically, as well as relative trajectories of liquid particles are identified. The dimensionless criteria for determining the hydrodynamic characteristics of a gas-liquid flow are proposed, particularly for determining trajectories of particles.

The pressure field is investigated on the extremum. As a result, local zones of pressure minimum are determined. It is established that the distances between adjacent zones of the pressure minimum are equal to the wavelength of the oscillatory impact of the moving wall to the flow. This fact indirectly proves further coagulation of droplets in these zones.

The abovementioned research does not consider the convective forces of inertia due to their significant nonlinearity. The impact of these forces to the hydrodynamics of a gas-liquid flow needs to be separately studied. Additionally, considering these forces leads to shifting local zones of pressure minimum from the flow core towards the oscillating wall due to the effect of vibrating weighting of particles, as well as changes the distances between droplets and the oscillating wall depending on a particle size. Moreover, particular interest is in the consideration of the vibrational effect on a turbulent flow and finding an approach for estimating frequencies of turbulent pulsations.

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