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HYDRODYNAMIC EFFECTS OF PULSING FLOWS OF TWO-PHASE MEDIA IN A CIRCULAR PIPE WITH VARIABLE CONCENTRATION AND PRESSURE

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Abstract: The article investigates the hydrodynamic effects of pulsating flows of two-phase media in a round pipe with variable phase concentrations, taking into account the change in the transverse pressure gradient. The model problem is solved numerically with the corresponding initial and boundary conditions taking into account the Womersley parameter and the Reynolds number.

Keywords: two-phase medium, pulsating motion, Richardson effect, marching method, Reynolds number, Womersley parameter, sticking conditions, pressure gradient.

Introduction

In recent years, the interest of researchers in the issues of pulsating flow of single and multiphase media has increased significantly. The scientific interest in this problem is due to the fact that pulsating flows of mixtures are increasingly being used in many branches of human activity.

Although a large number of scientific papers have been published on the hydrodynamics of pulsating flows, many issues have not yet been studied enough. These include, for example, unsteady motion of pulsating flows of multiphase media in pipes. Separate works and theories of the study of these processes, as a rule, are based on the use of simplified models.

Fundamental studies of such issues require the creation and selection of hydrodynamic models that actually reflect the physics of phenomena in the mixture, the development of universal algorithms and the use of modern computers to solve these problems, allowing a deeper study of the true picture of the processes under consideration.

E.G. Richardson and E. Tyler experimentally discovered characteristic features of profile of longitudinal velocity during periodic fluid motion in the pipe. Using heat-loss anemometer they have measured the time average quadratic value of velocity in various sections of pipe with oscillating flow. It was determined that the maximum velocity during flow oscillation is located not on axis of the pipe, but closer to the wall. This phenomenon in the literature is known as “annular” Richardson effect [1, 3]. Let us consider the “annular” Richardson effect for a two-phase flow with variable phase concentrations taking into consideration changes in transverse gradient of the pressure.

It is generally acknowledged that the most promising for the study of multiphase flows is the use of theory of interpenetrating continua [1]. According to this theory, the system of dimensionless equations for viscous two-phase mixtures taking into consideration the conversion of physical area into unit square has the form [1, 2]:

$$x_1^{\xi} f_i \frac{\partial u_i^j}{\partial t} + \sum_{k=1}^{2} x_1^{\xi} f_i u_i^k \frac{1}{(L)^{\delta_k^2}} \frac{\partial u_i^j}{\partial x_k} = -\frac{M}{a_i} x_1^{\xi} f_i \frac{1}{(L)^{\delta_k^2}} \frac{\partial P}{\partial x_j} +$$

$$+\frac{1}{a_i} \sum_{k=1}^{2} \left(1 + \frac{\delta_j^k}{3}\right) \frac{1}{(L^2)^{\delta_k^2}} \frac{\partial}{\partial x_k} \left(x_1^{\xi} f_i \frac{\partial u_i^j}{\partial x_k} \right) +$$

$$+\frac{1}{a_i} \sum_{k=1}^{2} \left(1 - \frac{5}{3} \delta_j^k \right) \cdot \frac{\partial}{L \partial x_k} \left(x_1^{\xi} f_i \frac{\partial u_i^{3-j}}{\partial x_{3-k}} \right) +$$

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$$\cdot + \frac{1}{a_i}\xi\psi_i^{\,j} + \frac{M}{\mathrm{Re}_i} x_1^{\xi} K\left(u_{3-i}^{\,j} - u_i^{\,j}\right) + Fr_2 x_1^{\xi} f_i;$$

(1)

$$\frac{\partial f_i}{\partial t} + \sum_{k=1}^{2} \frac{1}{(L)^{\delta_k^2}} \frac{\partial\left(f_i u_i^{\,k}\right)}{\partial x_k} + \xi \frac{f_1 u_i^1}{x_1} = 0;$$

(2)

$$f1+f2=1;$$

$i, j = 1.2.$ (3)

where:

$$\vec{\Psi}_i = \begin{Bmatrix} -\frac{2}{3}\sum_{k=1}^{2} x_1 u_i^k \frac{1}{(L)^{\delta_k^2}} \frac{\partial}{\partial x_k}\left(\frac{f_i}{x_1}\right) + \frac{2}{3}\frac{\partial}{L\partial x_2}\left(f_i u_i^2\right) - 2\frac{f_i u_i^2}{x_1} \\ -\frac{2}{3}\frac{\partial}{L\partial x_2}\left(f_i u_i^1\right) \end{Bmatrix}$$

$\alpha_i = R\sqrt{\varpi / \nu_i}$ - Womersley oscillating parameter of i[th] phase;

$\mathrm{Re}_i = RU_{cp}/\nu_i$ - Reynolds number of i[th] phase;

$Fr_2^{-1} = gR/U_{cp}$ - Froude number of 2[nd] phase

$M = \mu_1/\mu_i$ - dimensionless number;

X_1. X_2 – transverse and longitudinal coordinates;

K – coefficient of interaction between phases;

u_i^j – j[th] velocity component of i[th] phase;

f_i - concentration of i[th] phase;

P - pressure;

t - time;

μ_i - coefficient of dynamic viscosity of i[th] phase;

δ_i^k - Kronecker symbol;

ω - oscillation cyclic frequency;

ψ_i^j – j[th] component of $\vec{\psi}_i$ vector;

L – dimensionless quantity leading the physical area of flow to unit square;

$\xi = 0$ corresponds to a flat task, $\xi = 1$ axisymmetric.

$X_1 = r$, $X_2 = Z$, $u_1^{(2)} = u_1$, $u_2^{(2)} = u_2$, $u_1^{(1)} = v_1$, $u_2^{(1)} = v_2$

We formulate the initial and boundary conditions for the system of equations (1)-(3).

Suppose that at the initial moment the two-phase flow is at rest. Starting from t>0 pressure gradient of periodic form arises, which causes the occurrence of unsteady flow. If to this, we add the sticking conditions on the wall, as well as the symmetry conditions on the pipe axis, the initial and boundary conditions will take the following form:

at t=0: $u_i^j = 0$. $f_i = f_i^0$ for $0<x_1<1$. $0<x_2<1$;

at t>0: $x_2 = 0$: $P = A_0 + A_1 \cos \omega t$, $u_i^1 = 0$. , $f_i = f_i^0$ for $0<x_1<1$;

at $x_2 = 1$: $\frac{\partial u_i^2}{\partial x_2} = 0$. $U_i^1 = 0$; for $0<x_1<1$;

at $x_2 = 0$: $u_i^1 = 0$. $\frac{\partial u_i^2}{\partial x_2} = 0$. $U_i^1 = 0$; for $0<x_2<1$;

at $x_1 = 1$: $U_i^j = 0$; for $0<x_2<1$;

Taking into consideration the fact that at the inlet pipe section the pressure gradient is periodic function of time, the boundary

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conditions at $x_2=0$ for the longitudinal velocity of the carrier phase are determined from the average consumption rate in the form:

$$u_1^2 = u_{10}(A(\alpha)\cos\omega t - B(\alpha)\sin\omega t)$$

The physical-mechanical parameters of mixture of type water + solid particles are accepted as two-phase flow. The system of equations (1)-(3) is solved by the marching method, taking into account the initial and boundary conditions. The individual members of system of equations (1)-(3) are approximated as follows:

$$A\frac{\partial F}{\partial t}\Big/_{i,j} = A^S_{i,j}\frac{F^{S-1}_{i,j} - F^{S}_{i,j}}{\Delta t}$$

$$A\frac{\partial F}{\partial \xi}\Big/_{i,j} = A^S_{i,j}\frac{F^{S+1}_{i,j} - F^{S+1}_{i-1,j}}{\Delta \xi}$$

$$A\frac{\partial F}{\partial \eta}\Big/_{i,j} = A^S_{i,j}\frac{F^{S+1}_{i,j+1} - F^{S+1}_{i,j-1}}{2\Delta \eta}$$

$$\frac{\partial}{\partial \eta}(A\frac{\partial F}{\partial \eta})\Big/_{i,j} = \frac{A^S_{i,j+1}(F^{S+1}_{i,j+\frac{1}{2}} - F^{S+1}_{i,j}) - A_{i,j-\frac{1}{2}}(F^{S+1}_{i,j} - F^{S+1}_{j,j-1})}{\Delta \eta^2}$$

$$\frac{\partial}{\partial \eta}(A\frac{\partial F}{\partial \xi})\Big/_{i,j} = \frac{A^S_{i,j+1}(F^S_{i+1,j+1} - F^{S+1}_{i-1,j+1}) - A^S_{i,j+1}(F^S_{i+1,j-1} - F^{S+1}_{i-1,j+1})}{4\Delta\eta\Delta\xi}$$

$$\frac{\partial}{\partial \xi}(A\frac{\partial F}{\partial \eta})\Big/_{i,j} = \frac{A^S_{i+1,j+1}(F^S_{i+1,j+1} - F^S_{i+1,j-1}) - A^S_{i-1,j}(F^{S+1}_{i-1,j+1} - F^{S+1}_{i-1,j-1})}{4\Delta\xi\Delta\eta}$$

$$\frac{\partial}{\partial \xi}(A\frac{\partial F}{\partial \xi})\Big/_{i,j} = \frac{A^S_{i+\frac{1}{2},j}(F^S_{i+1,j} - F^{S+1}_{i,j}) - A^S_{i-\frac{1}{2},j}(F^{S+1}_{i,j} - F^{S+1}_{i-1,j})}{\Delta \xi^2}$$

Where *A* and *F* – various combinations of volumetric concentration, phase velocity components, pressure gradient and some constants.

Numerical calculations were carried out over a wide range of the Womersley frequency parameter and Reynolds number. As example of manifestation of Richardson effect for a two-phase flow, in Fig. 1 shown profiles of phase longitudinal velocities for $\alpha_1=5$. $\alpha_2=1.9$. $Re_1=174$. $Re_2=25$, as well as $\alpha_1=10$. $\alpha_2=3.8$ $Re_1=155.8$. $Re_2=22.4$ at $\omega t=0$. $\pi/2$. $K=50$. $\mu_1/\mu_2=0.062$.

From the figure it can be seen that at moderate numbers of Womersley oscillating parameter of carrier phase $(\alpha_1=5)$ at the time moment $\omega t=0$ (α1 = 5) (curve 1), those features that are specific for oscillating flows begin to appear on the phase velocities profiles. The maximum velocity is located at distance $x_1=0.2\text{-}0.3$ from the pipe wall, and at $\omega t=\pi/2$ (curve 3) it moves to the core of flow. The layer-by-layer change in the u_1-u_2 phase velocity difference uniformly increases in the direction of axis.

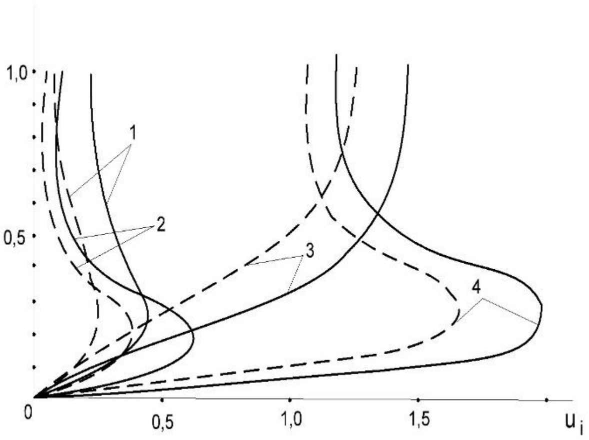

Fig. 1. Manifestation of Richardson effect for a two-phase mixture

Curves 2 and 4 obtained at $\alpha_1=10$ and $a_2=3.8$ clearly demonstrate the manifestation of "annular" Richardson effect for a viscous two-phase flow. The maximum values of axial components of phase velocities are moved closer to the wall. The relative difference u_1-u_2 is unevenly distributed over the section of pipe; it increases in the area of maximum values. Distribution diagrams of longitudinal velocities of phase obtained at time moment $\omega t=0$ differ from the profile taken at $\pi/2$. This is because the shape of the profile obtained at any time moment is certainly influenced by the velocity

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profiles that take place in the previous moments.

Results suggest that in the range of Womersley parameter α_1= 6….10 the particle transfer velocity is enhanced near the wall. Particles of the second solid phase migrate from the wall in the direction of the axis.

Table 1 shows the change in longitudinal velocity of the first phase along the axis of pipe depending on Womersley parameter and phase angle. With distance from the input, the change in axial velocity becomes smoother. It gradually grows to x_2 =0.5, after which it practically remains constant. Similar picture is observed for longitudinal component of velocity of the second phase on axis of the pipe (Table 2).

Table 1.

Change in longitudinal velocity of the first phase along the axis of the pipe depending on Womersley parameter

$\alpha_1 = 2.2$

x_2 \ ωt	0	$\pi/2$	$5\pi/6$	$5\pi/3$
0.05	0.8880	0.8858	-0.0064	-0.1758
0.10	0.9697	0.9710	0.1185	-0.1550
0.15	1.0627	1.1037	0.1798	-0.1482
0.20	1.1109	1.1764	0.2232	-0.1341
0.25	1.1393	1.2254	0.2489	-0.1218
0.30	1.1547	1.2546	0.2631	-0.1142
0.35	1.1627	1.2720	0.2706	-0.1010
0.40	1.1666	1.2819	0.2744	-0.1009
0.45	1.1685	1.2874	0.2762	-0.1008
0.50	1.1693	1.2880	0.2760	-0.1008

Table 2.

Change in longitudinal velocity of the second phase along the axis of the pipe depending on Womersley parameter

$\alpha_1 = 0.84$

x_2 \ ωt	0	$\pi/2$	$5\pi/6$	$5\pi/3$
0.05	0.6703	0.6374	-0.2285	0.7412
0.10	0.6730	0.6319	-0.2125	0.7241
0.15	0.6773	0.6325	-0.2001	0.7082
0.20	0.6797	0.6315	-0.1900	0.6862
0.25	0.6814	0.6307	-0.1822	0.6614
0.30	0.6826	0.6299	-0.1764	0.6524
0.35	0.6833	0.6292	-0.1722	0.6415
0.40	0.6838	0.6286	-0.1692	0.6404
0.45	0.6841	0.6382	-0.1671	0.6402
0.50	0.6843	0.6280	-0.1670	0.6402

Studies have shown that Richardson effect increases with increasing oscillation amplitude, and phase correspondence between shearing stress and velocity change in different layers of the flow is a function of the frequency parameter. With an increase in the frequency parameter, when an M-shaped profile of the longitudinal velocities of the phases is formed, the value f_2 begins to decrease in the wall layers of the flow. Moreover, the process of particle transfer from the wall layers increases with a decrease in the boundary layer. The strongly Richardson effect is pronounced, the lower the volume content of the second phase in the parietal layers. Thus, an increase in the Richardson effect decreases f_2 near the wall and increases the parietal peak of concentration of transported medium.

By virtue of Newton's law of viscous friction, the restructuring of the velocity profile during unsteady motion of the mixture should be accompanied by a change in the distribution law of shearing stresses in the flow. Due to the fact that during a pulsating flow near the pipe wall, a deviation of the velocity distribution from the quasistationary law increases with increasing Womersley parameter, the shearing stresses on the wall must also differ from their quasistationary values. In this regard, the study showed that when the phase velocity profiles have an M-shaped distribution, the shearing stress on the wall increases several times in comparison with the laminar flow. Moreover, the larger the boundary layer, the greater the shear stress on the wall and less in layers located closer to the axis. Taking into consideration the fact that with M-shaped distribution of velocities with pronounced Richardson effect, the predominant amount of fluid is near the wall and the shearing stress increases; then the fluid with a large volume concentration in the wall layers enhances the flushing properties of the flow and prevents particles from settling, and also reduces wear.

Therefore, decisive role of frequency parameter α_i in changing the distribution of velocities and volume concentration of phases and, as a consequence, in changing the shearing stress, allows considering parameter α_i as one of the main criteria for an unsteady pulsating flow. The ratios α_i in this case are considered as the product of the Reynolds and Strouhal numbers, in the calculation of which the values of the flow parameters are taken at the same time moments.

Consequently, it is possible to control the hydrodynamic parameters of the flow from the point of view of its efficient transportation by modulating pressure gradient over wide ranges of the parameter α.

Studies carried out regarding manifestation of Richardson effect have great practical importance in transportation of small-grained materials, coal-water mixtures, as well as in washing pipes from chemicals and fuels.

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