POSSIBLE INTENSIFICATION OF INTERPHASE HEAT AND MASS TRANSFER IN A GAS SUSPENSION WITH PULSATING RESONANCE FLOW

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Calculated motions and heat transfer of particles suspended in a gas stream pulsating at large amplitude (resonance) show that the heat transfer and the amount of heat transferred to a particle increases, while the mean flow velocity required to transport particles decreases in comparison with the corresponding values in flow without pulsation. The use of resonance oscillations is claimed to intensify interphase heat and mass transfer in a gas suspension.

The employment of a pulsating flow to intensify heat and mass transfer in gas suspensions, has already been proposed [2, 1, 9]. The matter was investigated experimentally in [2]. In [3] an analysis was made of the tests reported in [2], and calculations were performed showing that in many cases of practical importance, no noticeable intensification of heat transfer in the presence of pulsations is forthcoming.*

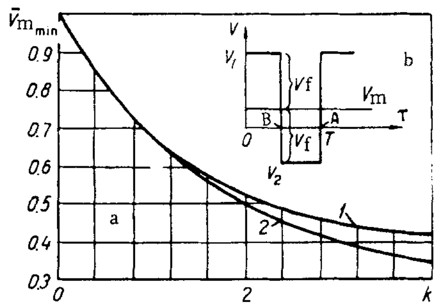

Fig. 1. Minimum mean velocity of pulsating resonant stream required to transport particles in the vertical direction (a), and a graph of the velocity of the pulsating stream (b): 1) $gT/V_s = 0.2$; 2) $gT/V_s = 0$.

The situation is different if the frequency of the gas velocity oscillations imposed by the pulsator coincide with the natural frequency of the gas in the system (drier tube, etc). The tests reported in [4] showed that in the pulsating gas flow along the tube, resonance velocity oscillation amplitudes arise which may be several times greater than the amplitude values remote from resonance and of the mean stream velocity. At the antinodes of the corresponding standing waves the instantaneous stream velocity vector at certain times is not only directed opposite the mean discharge velocity vector, but also is appreciably greater than the latter in absolute value. Of course, the mean modulus of the velocity of the resultant resonance pulsations (on which the intensity of heat and mass transfer also mainly depends) is considerably greater than the mean discharge velocity.

Resonance leads to increased heat exchange between the gas and the walls of the tube [5–7], as well as with cross-flow heating surfaces [4]. It may be supposed that the resonance flow oscillations have no less positive an influence on interphase heat transfer in a gas-suspension of large particles.* Results are given below of calculations which confirm this hypothesis. We shall use the approximate method of calculation adopted in [3].

The following simplifying assumptions are made:

1. A particle of constant mass moves vertically upwards, entrained by a gas stream whose velocity equals $V_1 = V_m = V_c$ in one half period T of the pulsations, and $V_2 = V_m = V_c$ in the other (Fig. 1b).

2. The specific weight of the medium (gas) is negligibly small in comparison with that of a particle.

3. Collisions of a particle with the walls and with other particles are not considered.

4. The aerodynamic drag and heat transfer of a particle are quasi-steady, i.e., at each instant of time they are calculated from relations obtained under steady conditions.

5. The drag coefficient Ψ of a particle does not depend on the gas velocity (self-similar region) and particle orentation.

It is necessary to determine the quantities Nu_m, τ_r and $Nu_m \tau_r$ at various values of the oscillation amplitude $k = V_c/V_m > 1$ (the case k = 1 was examined in [3]). It is precisely the condition k > 1 that

*As shown in [3], the minimum mean flow velocity required to transport large particles pneumatically in a pulsating flow is less than the velocity V_c in a flow without pulsations. This permits a decrease of mean velocity in the presence of pulsations and the use of the regime $V_m \approx V_c$ or even $V_m < V_c$. In these regimes the gain in residence time of a particle in the apparatus τ_r may prove to be greater than the loss in heat transfer coefficient α. Then the quantity $Nu_m \tau_r$, i.e., the amount of heat transferred, increases in the presence of pulsations [2, 3]. Owing to the danger of fallout of particles, however, the practical use of these regimes is inexpedient in many cases.

*Low volume concentrations of solids in the apparatus with the gas suspension evidently do not lead to substantial reduction of the effect obtained in tests [4] with single-phase flow.

describes the special features of oscillations at resonance.

We shall examine the so-called steady section (steady in the sense that the particle motion in each successive period does not differ from its motion in the preceding period). Then, using (1) and (2) of [3], it is not hard to show that when $\overline{T} = gT/V_c < 0.2$ and $k > 1$, the values of particle velocity at characteristic times A and B (Fig. 1b) are

$$u_B = \frac{[V_1(V_1 - u_A) - V_c^2]\,\overline{T}/2 + u_A V_c}{(V_1 - u_A)\,\overline{T}/2 + V_c},$$

$$u_A = \frac{V_c u_B - [V_2(V_2 - u_B) + V_c^2]\,\overline{T}/2}{V_c - (V_c - u_B)\,\overline{T}/2}, \qquad (1)$$

where

$$V_1 = V_m(1 + k), \quad V_2 = V_m(1 - k).$$

Solving the system of equations (1), and setting $\overline{T} \to 0$ as a first approximation, we obtain

$$\overline{u}_A = \overline{u}_B = \overline{u} = (\overline{V}_m^2 \cdot 2k - 1)/2\overline{V}_m k, \qquad (2)$$

where

$$\overline{u} = u/V_c, \quad \overline{V}_m = V_m/V_c.$$

We shall determine the minimum mean gas velocity required to transport the particles (the analog of velocity V_c in a flow without pulsations) by putting $\overline{u} = 0$ in (2):

$$\overline{V}_{m_{min}} = 1/\sqrt{2k}. \qquad (3)$$

Thus, with increase of relative oscillation amplitude, the velocity required for pneumatic transport of the particles decreases. It is appropriate to note that this reduction is due to the nonlinear dependence, assumed in the calculations, of drag force on velocity, and must be absent in the region $Re \leqslant 1$.

Calculations shows that our assumption of $\overline{T} \to 0$ does not lead to a large error in condition $\overline{T} < 0.2$. This is shown in Fig. 1a, which gives the values of $\overline{V}_{c\,min}$ obtained from an accurate solution of (1) at $\overline{T} = 0.2$ and according to (3).

The subsequent calculations are similar to those made in [3]. The mean value of Nu during the period is determined from

$$Nu_m \sim \frac{1}{2}\,[(V_1 - u)^n + (u - V_2)^n].$$

Since $Nu_0 \sim V_c^n$ in the flow without pulsations, it is not difficult to show the validity of the equation

$$\frac{Nu_m}{Nu_0} = \frac{1}{2}\left[\left(\frac{\overline{V}_m^2 \cdot 2k^2 + 1}{2k\overline{V}_m}\right)^n + \left(\frac{\overline{V}_m^2 \cdot 2k^2 - 1}{2k\overline{V}_m}\right)^n\right].$$

The relative residence time of the particle in the so-called steady section is found from the following relations: $\tau_r \sim 1/u$, expression (2) for the pulsating flow and the equality $u_0 = V_0 - V_c$ for the flow without pulsations:

$$\frac{\tau_r}{\tau_{r_0}} = \frac{2k\overline{V}_m(\overline{V}_0 - 1)}{2k\overline{V}_m^2 - 1}.$$

The further calculations were carried out for two cases: $\overline{V}_m = \overline{V}_0$ and $\overline{V}_m = \overline{V}_0/\sqrt{2k}$. The latter equality expresses the condition for the same margin of flow velocity (from the viewpoint of ensuring reliable pheumatic transport) in conditions of resonance oscillations and in flow without pulsations.

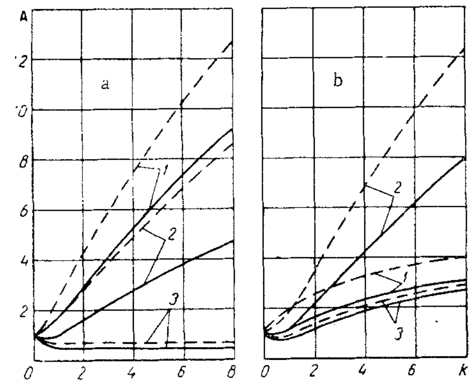

Fig. 2. Heat transfer and residence time of a particle in the apparatus with pulsating resonance flow of air in the "steady" section at $V_m = V_0$ (a), and $V_m = V_0/\sqrt{2k}$, $k > 1$ (b): 1) $A = Nu_m/Nu_0$; 2) $Nu_m\tau_r/Nu_0\tau_{r0}$; 3) τ_r/τ_{r0}; the broken lines are for $V_0/V_c = 3$, and the continuous lines for $V_0/V_c = 2$.

It was assumed that $n = 0.8$ and the cases $\overline{V}_0 = 2$ and $\overline{V}_0 = 3$ were examined. The results are shown in Fig. 2, from which it may be seen that when $\overline{V}_0 = \overline{V}_m$ a large gain is achieved in the value of Nu_m, while the value of τ_r decreases as the oscillation amplitude increases. At the same time, for the condition $\overline{V}_m = \overline{V}_0/\sqrt{2k}$, not only is the increase in the value of Nu_m/Nu_0 large, but the simultaneous increase in the value of τ_r leads to a considerably larger increase of the product $Nu_m\tau_r$ than in the first case, this determining the amount of heat transferred to (or given up by) the particle.

In this way, it is possible, with the aid of resonance oscillations, to reduce substantially the mean gas velocity, while simultaneously increasing the quantities Nu_m and $Nu_m\tau_r$, even without reducing the reliability of transport.

An examination has been made above of motion and heat transfer of a particle in the "steady" section. To complete the picture we shall evaluate the Nu_s number in the so-called accelerating section (in the early stages after the particle has entered the apparatus). We shall examine the limiting case $u = 0$, corresponding to the initial motion of a particle introduced into the apparatus with no initial velocity. Then it is not difficult to show the validity of the formula

$$\frac{\mathrm{Nu_m}}{\mathrm{Nu_0}} = \frac{1}{2}\left\{\left[\frac{V_m}{V_0}(1+k)\right]^n + \left[\frac{V_m}{V_0}(k-1)\right]^n\right\}. \quad (4)$$

The results of calculations according to (4) are shown in Fig. 3, from which it may be seen that under resonance oscillations of sufficiently large amplitude, the quantity $\mathrm{Nu_m}$ must also increase in the accelerating section.

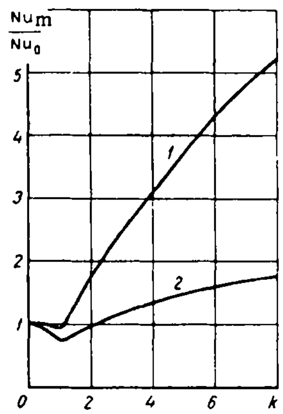

Fig. 3. Heat transfer of a particle at the start of acceleration: 1) $V_m = V_0$; 2) $V_m = V_0/\sqrt{2k}$; $k > 1$.

Our calculations were made assuming quasi-steady Nu. Therefore, on the basis of the data of [8], it may be assumed that the values of $\mathrm{Nu_m/Nu_0}$ obtained are minimal, and may be increased at appropriate values of the parameters.

The object of this paper is to explain the possibility, in principle, of intensifying heat transfer by resonance pulsations. No account has been taken, therefore, of variation of oscillation amplitude along the channel, the fact that the flow may not be isothermal, etc. It may be assumed however, that the results obtained correctly reflect the basic features of the motion and heat transfer of the particle in the flow at values $k > 1$. For example, it is not difficult to show the possibility of pneumatic transport at values $V_m < V_c$ and in conditions when the pulsation waveform deviates from rectangular, if, as in the case examined, the dependence of the drag force of the particle on gas velocity is nonlinear.

Thus, the prospect of producing apparatus with resonance pulsations on the transporting agent deserves careful study. In order to improve the economics of such apparatus, the additional energy expenditure associated with pulsator operation should be a minimum. This may be attained by using an efficient pulsator design, by tuning the system to the optimum oscillation frequency (from the viewpoint of hydraulic losses), and using twin tubes with alternating gas supply to each. The latter should also ensure that the total hydraulic resistance of the system is constant.

There is no doubt that to create an actual piece of equipment it is necessary to solve a number of further problems, including correct choice of the point at which to introduce the material into the apparatus, and determination of the gas oscillation amplitude in systems of various types, etc.

NOTATION

d—particle diameter; f and T—frequency and period of pulsations; $k = V_f/V_m$—dimensionless pulsation amplitude; V—gas velocity; V_1 and V_2—gas velocity at different sections of oscillation period (Fig. 1); V_s—critical velocity; u—particle velocity; τ—time; τ_r—residence time of particle in apparatus in the "steady" section; Ψ—drag coefficient. Subscripts : 0—in flow without pulsations; m—mean over period; A and B—values at points A and B (Fig. 1); min—value for zero mean motion of particle over period; a bar over a letter denotes a dimensionless quantity.

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