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HYDRAULIC RESISTANCE AND HEAT TRANSFER IN A PULSATING FLOW OF A GAS – SOLID MIXTURE

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It is shown that the heat-transfer coefficient can be increased by 30-35% if periodic fluctuations in speed occur in an ascending gas–solid mixture.

Much importance has recently been attached [1] to pulsed pneumatic transport, in which there is a strictly periodic air input into a pipeline. This provides similar speeds for the carrying medium and bunches of material, which provide for considerably improved range and performance.

On the other hand, forced velocity pulsation superimposed on a uniform flow may accelerate heat transfer [2, 3], while colliding jets of suspensions and pulsations in ascending gas–solid flows at resonance may accelerate heat transfer between phases [4].

Here we report measurements on velocity pulsations and heat transfer for gas–solid suspensions in pipes.

The equipment has previously been described [5]; the velocity fluctuations were produced by periodically altering the cross section of the pipe before or after the working section, which was a steel tube of internal diameter 8 mm and length 800 mm. The pulsation frequency was in the range 1-12 Hz and was recorded by a clock system (1 Hz) or by a stroboscopic tachometer (5 or 12 Hz). The amplitude of the pulsations in the flow rate was estimated from the fluctuations in the stagnation pressure. The Reynolds number varied in the range $(2\text{-}8.2)\cdot 10^3$, while the corresponding gas speeds were 4.6-17.5 m/sec. The electrocorundum particles of diameter 60 μ were used at concentrations from 0 to 11 kg/kg. The value did not exceed 6 kg/kg at low gas speeds.

The time-averaged pressure difference over the working section was measured with a micromanometer.

The studies amounted to determining the empirical factor K applicable to the resistance due to the particles in the flow.

The definition of K is as follows [6]:

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TABLE 1. Experimental Values of the Coefficients K and K_p Calculated from Eq. (1)

Flow mode	f, Hz	Re	μ, kg/kg	K	K_p
Laminar	0	1000—5000	0,8—15,0	$0{,}34 \cdot 10^8 \cdot \mathrm{Re}^{-2.3}$	—
	1; 5	2000—3800	2; 5—11,0	—	$1{,}18 \cdot 10^3 \cdot \mathrm{Re}^{-2.5}$
	12	2000—3600	3,0—10,0	—	$1{,}44 \cdot 10^8 \cdot \mathrm{Re}^{-2.5}$
Turbulent	0	5000—8000	1,0—15,0	0,2	0,2
	1; 5	4000—8200	3,0—9.0	—	0,25
	12	3600—8000	3,0--9,0	—	

$$K = \frac{\Delta P_{mix}/\Delta P_a - 1}{\mu} \qquad (1)$$

which applies for pulsating and steady flows. The pressure difference ΔP_{mix} was measured in the hydrodynamic-stabilization section and corrected for energy loss due to particle lift, while ΔP_a was calculated from standard relations for clean air in smooth tubes. Table 1 gives the results. The laminar and turbulent modes have substantially different values for the characteristics, which themselves determine the transport rates. This effect is fairly clear, although not seen directly, and can serve to define the mode of flow; in that way one can estimate the critical value of Re, e.g., from the Re dependence of Eu and Nu. Curves of Nu = f(Re) type for the clean gas, and for the steady-state and pulsating suspension flows, allow one to determine the effects of the particle concentration and pulsation frequency on the critical Re [5]. Table 1 shows that the range in Re for laminar or turbulent flows varies somewhat with f.

There is an exponential fall in K down to the level of Re corresponding to onset of turbulence for f = 12 Hz and for f = 0, but thereafter there is very little velocity dependence. For instance, for a steady-state flow ($\mu \leq 15$ kg/kg) and for a pulsating one ($\mu \leq 3$; f = 12 Hz) the values of K fell in the first case from 1.4 to 0.2 as the Reynolds number increased from 1000 to the critical value of 5000, while in the second case the fall to K = 0.2 occurred already at Re ≈ 3600, with little further change in K, i.e., the forced oscillations have little effect at high speeds, and K can be taken from the usual formulas [6] to a first approximation.

Also, pulsations superimposed on a gas containing only a little material ($\mu \leq 2$ kg/kg) result in the K = f(Re) curves splitting up in accordance with the solid content; in that case, K is larger by a factor of 2-3 than at higher contents, which is due to the more marked effect of the pulsations on the pressure difference at low concentrations.

Figure 1 shows the changes in the relative pressure difference over the section in relation to particle content for steady-state and pulsating flows; in the first case, $\Delta P_{mix}/\Delta P_a$ increases with the concentration and is dependent on the speed, being largest for the laminar state (curves IV). In the turbulent state (curves V and VI), the relative drop is larger than that in the transition region (curve VII). A pulsating flow at low speeds (Re = 2000, curve I) gives the loss in pressure as dependent only on the concentration, whereas the transitional and turbulent modes show an effect from the pulsation frequency, since the loss increases with the latter. Curve II corresponds to 12 Hz and curve III, to 1 and 5 Hz.

In the transition region, $\Delta P_{p.\,mix}/\Delta P_a$ is independent of the frequency and takes the values for steady-state flows; the pulsations cause the relative pressure drop to be higher for Re = 2000 even for f = 12 Hz. At low frequencies, the pressure difference is the same as that for the steady-state case within the error of measurement. A relationship has been reported [5] between the critical Reynolds number and the solid content, and it has been found that the stability of a laminar steady-state flow is perturbed for Re around 10^3 and $\mu \leq 4$ kg/kg; any further increase in the concentration causes the critical Re to be above that for pure air. If pulsations are imposed on a mixture $\mu > 4$, Re_{cr} shifts to higher values, i.e., the pulsations have the same effect as a concentration increase. For instance, a pulsating flow with $\mu = 5$ kg/kg and f = 5 Hz gave $\mathrm{Re}_{cr} \approx 3800$, while for f = 0 this value of Re_{cr} was attained at $\mu = 16$ kg/kg.

Therefore, these pulsations suppress the turbulent small-scale velocity fluctuations, as do increased particle concentrations, with the result that the laminar flow persists to higher speeds [8]. On the other hand, turbulence sets in earlier at any concentration under our conditions at low frequencies, e.g., at Re = 5000 (the equivalent for clean gas is taken as 10^4). There is a transition range Re = 3800-5000, which becomes narrower at high frequencies,

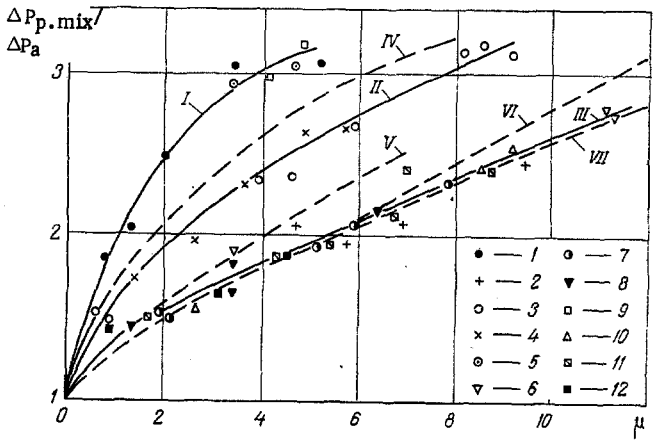

Fig. 1. Dependence of pressure difference in pulsating flow of mixture on particle concentration; f = 12 Hz: 1) Re = 2000; 2) 3400; 3) 5000; 4) 8000; f = 5 Hz: 5) Re = 2000; 6) 3400; 7) 5000; 8) 8000; f = 1 Hz; 9) Re = 2000; 10) 3400; 11) 5000; 12) 8000. [V) Re = 8000; VI) 5000; VII) 3400].

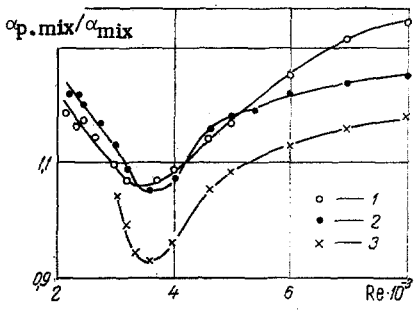

Fig. 2

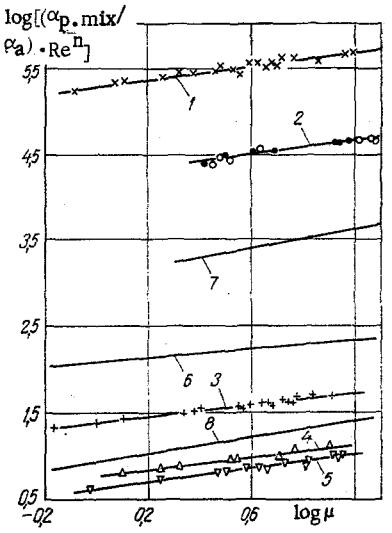

Fig. 3

Fig. 2. Dependence of relative heat-transfer coefficient on flow speed for f = 5 Hz: 1) μ = 3 kg/kg; 2) 5; 3) 8-10.

Fig. 3. Generalized dependence on heat transfer. Pulsating flow: laminar mode – 1) f = 12 Hz; 2) 1 and 5 Hz; turbulent and transitional modes – 3) f = 12 Hz; 4) 5; 5) 1. Steady-state flow [5]: 6) laminar mode; 7) transitional; 8) turbulent.

and which at f = 12 Hz vanishes altogether. A qualitatively similar result (no transitional mode) was reported in [8], where the laminar mode was replaced suddenly by the turbulent one at Re = 5000 for μ = 25 kg/kg.

The effects of the forced oscillations on the heat transfer as a function of speed are shown in Fig. 2 for f = 5 Hz; the heat-transfer rate tends to fall as the velocity increases up to about Re ≈ 3800, and then it rises, and the effects of the pulsations are the less, the larger the particle concentration. Relative heat-transfer coefficients increase from 1.2 to 1.35 on raising the frequency from 1 to 12 Hz in the laminar mode with μ = 5 kg/kg, which occurs because the pulsations in the gas phase play a larger part, and heat transfer for clean air is maximal for f = 12 Hz. Conversely, developed turbulence causes $\alpha_{p.mix}/\alpha_{mix}$ to fall from 1.35 to 1.0, which is clearly due to the dominant role of turbulent-pulsation transport.

TABLE 2. Values of Constants in Eq. (2)

Flow mode	Pulsation frequency f, Hz	Re	μ, kg/kg	c	n	m
Laminar	1	2000—3800	2,5—10,0	$2,16 \cdot 10^4$	—1,22	0,363
	5	2000—3800	2,5—11,0	$2,3 \cdot 10^4$	—1,22	0,292
	12	2000—3600	0,8—10,0	$19,5 \cdot 10^4$	—1,50	0,350
Turbulent	1	4000—8200	1,0—9,0	4,26	—0,20	0,401
	5	4000—8200	1,2—9,0	5,71	—0,23	0,376
	12	3600—8000	0,7—9,0	25,3	—0,40	0,305

Contents above 8 kg/kg cause the heat-transfer rate to fall, and the relative heat-transfer coefficients are less than 1 at the maximum frequency used in our experiments. The same results have been obtained for clean air at f = 20 Hz [7]. Table 2 shows that the relevant heat-transfer coefficients are most markedly dependent on the speed in the laminar mode, which results in a more marked fall than that occurring in the steady state, where $\alpha_{p.mix}/\alpha_a \sim Re^{-0.55}$. The effects of Re on the heat transfer in a pulsating flow are similar for horizontal transport with f = 0, where $\alpha_{mix}/\alpha_a \sim Re^{-1.20}$ [5]. The effects of the concentration on $\alpha_{p.mix}/\alpha_a$ vary with the frequency and speed only to small extents, namely, from 0.3 to 0.4, as Fig. 3 shows, which presents the generalized experimental data. For comparison we give the approximating straight lines derived for a steady-state ascending flow [5]. Figure 3 shows clearly the effects on the heat-transfer rate in various modes of flow with superimposed periodic pulsation; in the turbulent mode (Re > 5000) the effects of speed and concentration are only slight, whereas in the laminar case the velocity has a much more marked effect on the heat transfer.

Least-squares fitting gave the following working formula with an error of less than 6%:

$$\frac{\alpha_{p.mix}}{\alpha_a} = c\,Re^n \mu^m. \qquad (2)$$

The values of c, n, and m are given in Table 2; the heat-transfer coefficient α_a was derived from the formulas of [7].

These results on the hydrodynamics and heat transfer in pulsating motion in vertical tubes show that such pulsations for $\mu > 4$ tend to suppress the laminar made and to reduce Re corresponding to onset of developed turbulence for all μ, which provides some explanation of observations on the pulsation processes in dispersed flows. The effects of the speed on the heat transfer are substantially dependent on the mode of flow.

NOTATION

ΔP_{mix} is the pressure drop with mixture in tube, N/m^2;
ΔP_a is the pressure drop for pure air;
$\Delta P_{p.mix}$ is the pressure drop for pulsating flow of mixture;
G_t is the mass flow rate of particles, kg/h;
G_a is the mass flow rate of air;
$\mu = G_t/G_a$ is the ratio of mass flow rates;
Re is the Reynolds number;
Re_{cr} is the critical Reynolds number;
f is the frequency of velocity pulsations, Hz;
α_v is the heat-transfer coefficient in steady-state flow, $W/m^2 \cdot °C$;
α_a is the heat-transfer coefficient for pure air;
$\alpha_{p.mix}$ is the heat-transfer coefficient for pulsating flow of mixture;
K is the coefficient for resistance caused by particles.
K_p is the coefficient for pulsation-frequency effect and resistance due to the particles [$K_p = (\Delta P_{p.mix}/\Delta P_{a-1})/\mu$].

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HOT-WIRE METHOD IN A NONSTATIONARY VARIATION

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Starting from the solution of the thermal-conductivity equation, a nonstationary variation of the "hot-wire" method is developed in the case of monotonic heating of a calorimetric system which permits determination of the temperature dependence of the thermal conductivity of liquids in a broad temperature range from one test.

The stationary "hot-wire" method is extensively used at this time to investigate the coefficient of thermal conductivity of gases and liquids [1]. This method, as all stationary methods (plane layer, coaxial cylinders), is distinctive in the long duration of the test, requires a complex apparatus, and does not permit determination of the temperature dependence of the coefficient of thermal conductivity from one test. Using this method, the experimenter should expect the buildup of a stationary state in a calorimetric system every time when measuring the coefficient of thermal conductivity. Consequently, the determination of the coefficient of thermal conductivity of one liquid in a broad temperature range takes several days at a minimum. Hence, several, principally foreign, papers devoted to a nonstationary variation of the "hot-wire" method have recently appeared [2-15]. The theory of the method in application to rarefied gases is elucidated in especial detail in [16]. The "hot-wire" method differs from all other nonstationary methods in that the coefficient of thermal conductivity is determined directly by this method, and not the coefficient of thermal diffusivity. However, it is not very exact because of the difficulty of recording exactly the rapidly varying wire temperature during the measurement. In this respect, the method mentioned in the relative variation in which the recording device acts as a zero indicator [17] is of definite interest.

An attempt is made below to extend the "hot-wire" method to the case of a monotonic change in the temperature of a calorimetric system.

The design scheme of the method under consideration reduces to the following. A fine metal wire of radius R_i (Fig. 1) is stretched coaxially in a bulky metal tube 1 of radius R_0 through a sealed electrical insulating plug 2. The liquid being investigated fills the gap between the wire 3 and the tube 1. A constant-power electrical current passes through the wire during the entire test. In the stationary variation of the method, the whole system (module) is strictly thermostated.

Let us assume that the whole system is surrounded by a heat-insulating shell which rises smoothly in temperature under the effect of the external heater 4 in such a way that the temperature of the shell approximately equals the temperature of the module. In this case the heat flux of the inner heater 3 is expended completely in a slow rise in the temperature of the module and the liquid. The power $W(\tau)$ of the Lenz–Joule heat developed by the wire, the temperature drop $\vartheta(\tau)$ in the layer under investigation, and the rate of temperature rise $b(\tau)$ of the system are measured in the test.

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