HEAT TRANSFER OF GAS-SUSPENSION FLOW IN HORIZONTAL AND VERTICAL TUBES

V. V. Mamaev, V. S. Nosov,
N. I. Syromyatnikov, and V. S. Barbolin

UDC 536.244:532.582.7

It is shown experimentally that the heat transfer to a dusty gas flow is significantly influenced by the flow conditions and the tube orientation.

The vast majority of studies of heat-transfer processes in a disperse current of gas and solid particles have investigated turbulent flow of the mixture in vertical channels [4, 5]. At the same time, it is known that for apparatus with a two-component heat carrier the greatest energetic efficiency is obtained at the minimum gas velocity that is stable for the given concentration of solid phase. In this case, the intensity of heat exchange may be greatly affected by the direction of flow, and the extent to which the particle concentration and the gas velocity influence the heat-transfer coefficient will change significantly depending on the flow conditions. This explains the difference in the effect of gravity on the behavior of solid particles in vertical and horizontal tubes, especially at small Reynolds numbers; the change in the velocity and concentration profiles of the flow; and the marked effect of free convection under laminar flow conditions.

Experiments on the heat transfer to an air current carrying synthetic-corundum particles (diameter 60 μ) were carried out on an apparatus of open-circuit type [1]. The air was pumped through a receiver, a measuring diaphragm, a rotor dust-feeder, and the working part of the tube, and, after dust removal in a fabric filter, was released to the atmosphere. The mass flow rate of the air was varied in the range 0.2-3.7 kg/h. The mean gas velocity over the total cross section of the working part of the tube was 2.5-18.0 m/sec in the experiments with dust, corresponding to a variation in Reynolds number between 10^3 and $8 \cdot 10^3$. The flow rate of solid phase was determined both from the output of the dust feeder and by weighing the filter at known intervals. The concentration of particles in the air current varied from 0 to 25 kg/kg for a horizontal tube and from 0 to 15 kg/kg for a vertical tube. The working part was a steel tube of internal diameter 8 mm and length 800 mm, to the outside of which was fitted a 500-W Nichrome electric heater. The outer diameter of the working part, taking into account the layer of heat insulation, is 50 mm. The temperature of the current and the tube walls was measured by an XA-type thermocouple, the emf of which was recorded using a PP-63 potentiometer. All of the experiments were carried out in the steady state, for constant heat-flow density over the length of the channel.

Some results were given in [1] for the heat transfer of the gas suspension when the working part was horizontal.

The numerical values of $\mathrm{Re}_{\mathrm{cr}_1}$ and $\mathrm{Re}_{\mathrm{cr}_2}$, which reflect the transition from one set of flow conditions to another, were estimated from the change in the dependence of the heat-transfer coefficient on the air velocity at different values of the dust concentration, as explained in more detail in [1].

Under these conditions, laminar flow is retained until $\mathrm{Re}_{\mathrm{cr}_1} = 2200$, and relatively developed turbulent flow begins at $\mathrm{Re}_{\mathrm{cr}_2} = 5000$. The experiments with the gas suspension showed that for all orientations of the tube the value of $\mathrm{Re}_{\mathrm{cr}_1}$ depends significantly on the concentration of solid particles, whereas the value of $\mathrm{Re}_{\mathrm{cr}_2}$ remains unchanged. The dependence of the critical Reynolds number $\mathrm{Re}_{\mathrm{cr}}$ on the concentration μ of solid particles in the air current is not monotonic (see Fig. 1). In the absence of solid particles ($\mu = 0$), $\mathrm{Re}_{\mathrm{cr}_1}$ is 2200, but with increase in μ to 4 kg/kg, $\mathrm{Re}_{\mathrm{cr}_1}$ falls to 1200 for a horizontal tube and to 1500 for a vertical tube. Thus, for small concentrations of fine but sufficiently heavy corundum particles, laminar flow of the gas suspension becomes unstable even for Reynolds numbers of order 10^3. It is evident that under these conditions the main mass of particles is concentrated at the channel wall (small velocity gradient at the wall for small Re) and a role is played by surface asperities, which lead to the formation of gas eddies in individual parts of the

---

S. M. Kirov Ural Polytechnic Institute, Sverdlovsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 31, No. 4, pp. 613-618, October, 1976. Original article submitted August 26, 1975.

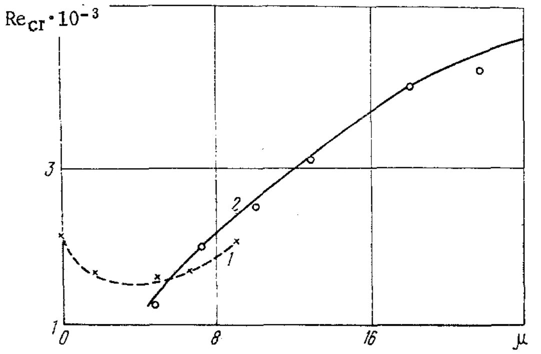

Fig. 1

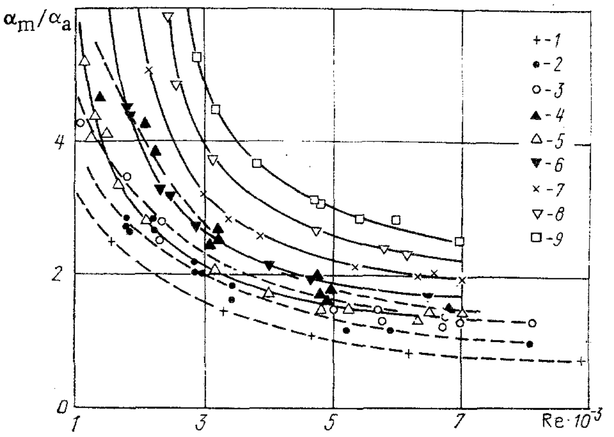

Fig. 2

Fig. 1. Dependence of critical Reynolds number on concentration of solid particles: the dashed curve is for a vertical tube and the continuous curve, for a horizontal tube; 1 and 2 are for Re_{cr_1}.

Fig. 2. Dependence of relative heat-transfer coefficient on gas velocity. The dashed curve is for a vertical tube: 1) μ = 2-3 kg/kg; 2) 5; 3) 6-7; 4) 8-10. The continuous curve is for a horizontal tube; 5) μ = 4.5-6 kg/kg; 6) 7; 7) 10-11; 8) 12-14; 9) 18 kg/kg.

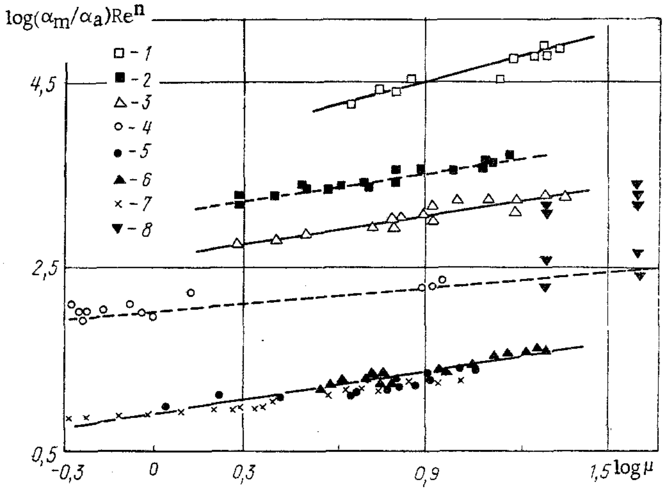

Fig. 3. Generalized heat-transfer curves. The dashed curves are for a vertical tube; 2) transitional conditions; 4) laminar; 5) turbulent. The continuous curves are for a horizontal tube: 1) laminar conditions; 3) transitional; 6) tubulent; 7) data of [3]; 8) data of [2].

tube. When the tube is horizontal, the possibility of precipitation of the particles on the lower surface means that the instability of the laminar gas flow is more pronounced.

With further increase in the solid-phase concentration ($\mu \geq 5$), the particles gradually saturate the flow nucleus, so that velocity pulsations originating close to the wall are damped near the channel axis [4, 5]. In short, the onset of turbulent conditions is postponed until Re_{cr_1} = 5000 for $\mu \geq 25$ kg/kg. Naturally, these limits would be somewhat different if the experiment were carried out for other conditions. It is very interesting that for large μ the transitional region of gas-suspension flow is practically absent, i.e., there is an abrupt change from laminar to turbulent flow over the whole length of the tube on reaching (under our conditions) Re ≈ 5000. Earlier [6], it was established that, at Re > 5000 and for a concentration μ = 25 kg/kg of graphite particles, there is a sharp discontinuity in the dependence of the heat-transfer coefficient on the solid-phase flow rate, which confirms to some extent what was said above on the abrupt character of the change in the hydrodynamic conditions of flow for a gas suspension (and also other two-component mixtures) in a channel at a given value of the discrete-phase concentration.

TABLE 1. Values of Constants in Eq. (1)

Flow conditions	Position of tube	Re	μ, kg/kg	$c\cdot10^{-3}$	n	m
Laminar	Horizontal	1100—4500	4,5—25,0	4,3200	—1,20	1,00
Laminar	Vertical	1000—2020	0,5—10,0	0,1135	—0,55	0,30
Transitional	Horizontal	1300—5000	1,8—25,0	0,4310	—0,75	0,50
Transitional	Vertical	1700—5000	1,8—15,0	1,2300	—0,90	0,50
Turbulent	Horizontal and vertical	5000—8000	1,0—25,0	0,0083	—0,3	0,47

Similarly, the theoretical investigation in [7] also showed earlier turbulization of the disperse flow.

Individual dependences of the relative heat-transfer coefficient α_m/α_a on the Reynolds number calculated from the velocity and viscosity of pure air are shown in Fig. 2. For $\mu > 2$, irrespective of the channel orientation or the velocity and conditions of flow, the heat-transfer coefficient is higher for a dusty gas flow than for a pure gas flow, for the same value of Re. It is important to stress that as the gas velocity increases, the role of the solid particles in intensifying the heat transfer tends to diminish; this was observed earlier in analyzing experimental data on the heat transfer of a turbulent flow [4, 6], but it was impossible to draw a general conclusion.

As is evident from Fig. 2, the negative effect of increase in velocity on the value of the relative heat-transfer coefficient is largest for laminar and transitional flow and is more pronounced for a horizontal tube.

Reduction in both the relative and absolute values of the heat-transfer coefficients with increase in the velocity of the dusty gas flow for Re < 5000 may be attributed to the Bernoulli effect, in which, in a two-phase flow, the less dense phase is more rapidly accelerated and, for a nonuniform velocity distribution over the cross section, there is a tendency to cluster close to the channel axis. Thus, for laminar and transitional flow, the concentration of fine particles is less at the flow nucleus than in the region at the wall. This, by the way, is the reason for the more considerable (in comparison with turbulent conditions) intensification of the heat-transfer process due to the hydrodynamic effect of the particles on the layer of gas at the wall. With increase in velocity at constant μ, the concentration field, like the velocity field, tends to equalize, and the Bernoulli effect is reduced.

Redistribution of particle concentration over the cross section leads to an increase in the thermal resistance of the flow nucleus (the concentration rises) and an increase in the thermal resistance of the layer at the wall (the concentration falls). In short, a decrease in the heat-transfer coefficient α_m is observed, especially for a horizontal tube.

For turbulent conditions in both horizontal and vertical tubes, $\alpha_m/\alpha_a \sim \mathrm{Re}^{-0.3}$, i.e., in this case the value of α_m increases with rise in Re, although (in good agreement with the data of [1, 6]) less than for pure air.

Hence, the addition of solid particles to a laminar gas flow may give the best results in terms of energy, but at the same time it is difficult to obtain a high absolute value of the heat-transfer coefficient.

The effect on heat-transfer intensity of the extent to which the flow is saturated by solid particles also changes on passing from laminar to turbulent conditions and depends on the direction of flow. The maximum value of the relative heat-transfer coefficient α_m/α_a is obtained for laminar flow. Thus, for example, for Re = 2000 and $\mu \approx 10$ kg/kg, the value of α_m/α_a is 6 for a horizontal tube and 4 for a vertical tube, while for Re = 7000 (turbulent conditions) the values are 2 and 1.5, respectively. For a vertical tube, the dependence of the heat-transfer coefficient on the value of μ changes insignificantly on passing from laminar to turbulent flow. This evidently indicates a more uniform distribution of particles over the tube. In horizontal tubes, the picture is different. For Re < 2000, the ratio $\alpha_m/\alpha_a \sim \mu^{1.0}$; for transitional conditions, $\alpha_m/\alpha_a \sim \mu^{0.5}$; and for Re ≥ 5000 (turbulent flow), as also in the case of a vertical tube, $\alpha_m/\alpha_a \sim \mu^{0.47}$. This change in the effect of μ is evidently associated with an extremely nonuniform distribution of particles over the channel cross section for small gas velocities and with gradual equalization of the concentration as the velocity increases.

A generalization of the experimental data is shown in Fig. 3, which includes the experimental results of [2, 3]. Experimental points corresponding to [2] for Re = 200-5000 and μ = 17-66 kg/kg (vertical channel) lie between the curves corresponding to laminar and transitional flow. The data of [3] are in satisfactory agreement with the correlation obtained for turbulent flow.

Analysis of the results using dimensionless numbers gives the calculational dependence

$$\frac{\alpha_m}{\alpha_a} = c\,\mathrm{Re}^n \mu^m. \qquad (1)$$

The values of the constants c, n, and m are given in Table 1.

Thus, the experimental results obtained demonstrate that there is a significant change in the extent to which the gas velocity and the particle concentration affect the heat-transfer coefficient of a disperse current on passing from laminar to turbulent flow. In a number of cases this may be the main cause of the discrepancy between results obtained by different workers.

NOTATION

μ is the concentration of solid particles in air, kg/kg;
α_a is the heat-transfer coefficient of air, $W/m^2 \cdot {}^\circ C$;
α_m is the heat-transfer coefficient of mixture of air and solid particles, $W/m^2 \cdot {}^\circ C$;
Re_{cr_1} is the Reynolds number characterizing the change from laminar to transitional flow;
Re_{cr_2} is the Reynolds number characterizing the change from transitional to turbulent flow.

LITERATURE CITED

1. V. S. Nosov, Proceedings of the S. M. Kirov Ural Polytechnic Institute [in Russian], No. 227, Sverdlovsk (1974), p. 61.
2. W. Danziger, Industr. Eng. Chem. Process Design Develop., 2, No. 4 (1963).
3. L. Farbar and M. Morley, Industr. Eng. Chem., 49, No. 7 (1957).
4. Z. R. Gorbis, Heat Transfer and Hydromechanics of Disperse Continuous Flows [in Russian], Énergiya, Moscow (1970).
5. S. Hsü, Hydrodynamics of Multiphase Systems [Russian translation], Mir, Moscow (1971).
6. N. I. Syromyatnikov and V. S. Nosov, Dokl. Akad. Nauk SSSR, 163, No. 3 (1965).
7. Yu. A. Buevich and V. M. Safrai, Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1968).

HEAT AND MASS TRANSFER OF LARGE DROPLETS IN HIGHLY TURBULENT FLOWS

R. S. Tyul'panov

UDC 536.422.4

A model is proposed for the heat and mass transfer of spherical bodies and large droplets in a strongly turbulent gas flow, when the scale of the turbulence is larger than the diameter of the body. Theoretical formulas are compared with experimental results.

The motion of a droplet in a gas flow in different kinds of technological equipment, including power installations, is accompanied by evaporation and by heat exchange with the surrounding gaseous medium. For large drops which are not involved in turbulent velocity pulsations, when the flow is characterized by the condition $L > d$ (L is the scale of the turbulence and d is the diameter of the body), the heat and mass transfer have certain specific properties.

In a number of works on the heat and mass transfer of a body in a gas flow, the processes appearing in the above conditions were found to be strongly influenced by the intensity of turbulence ε.

For a cylinder, the maximum value of Nu was observed for $L/d \simeq 1.6$, and on this basis a resonance theory of transfer was developed [1, 10].

Leningrad Technological Institute of the Cellulose and Paper Industry. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 31, No. 4, pp. 619-625, October, 1976. Original article submitted July 23, 1975.