LITERATURE CITED

1. N. V. Antonishin, M. A. Geller, and V. I. Ivanyutenko, "Heat transfer in a fluidized bed," Inzh.-Fiz. Zh., 41, No. 3, 465-469 (1981).
2. Yu. A. Buevich, "Approximate statistical theory of fluidized beds," Zh. Prikl. Mekh. Tekh. Fiz., No. 6, 35-47 (1966).
3. G. A. Korn and T. M. Korn, Manual of Mathematics, McGraw-Hill (1967).
4. O. M. Todes, N. V. Antonishin, L. E. Simchenko, and V. V. Lushchikov, "Analysis of the feasibility of describing the nonsteady thermal conductivity of dense disperse systems with differential equations allowing for features of the phase interaction," Inzh.-Fiz. Zh., 18, No. 5, 815-822 (1970).
5. V. I. Ivanyutenko, N. V. Antonishin, and V. S. Nikitin, "Expansion and porosity of a nonuniform fluidized bed," Inzh.-Fiz. Zh., 41, No. 3, 470-475 (1981).
6. N. I. Gel'perin, V. G. Ainshtein, and A. V. Zaikovskii, "Mechanism of heat exchange between a surface and a nonuniform fluidized bed of granular materials," Khim. Promst., No. 6, 18-26 (1966).

HEAT TRANSFER OF A SWIRLED FLOW OF GAS SUSPENSION IN A SHORT CHANNEL

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On the basis of generalized experimental data obtained by the method of local modeling, the article suggests a method of calculating the heat transfer of a swirled flow of gas suspension in a short channel.

Sharafutdinov et al. [1] examined the results of the experimental investigation of the heat transfer of a swirled flow containing dust particles of aluminum oxide 1-11 μm in size in a short partitioned pipe, the partitioning corresponding to the chamber of a rocket engine. The heat-transfer coefficients were determined by the gradient method with the aid of a cylindrical experimental section 0.18 m long and with inner diameter d = 0.106 m. Swirling of the flow was effected by swirlers with straight vanes [2] which were mounted ahead of the cylindrical experimental section 2 at a distance of 0.135 m (Fig. 1). The length of the passive heat-insulated section was L_0 = 2.91 m, the distance between the beginning of the heat-insulated pipe and the swirler was L_1 = 2.775 m. Behind the cylindrical experimental section there was the adapter 3, 0.114 m long, and the nozzle section 4 whose profile consisted of circular arcs. The diameter of the critical nozzle section was d_{cr} = 25 mm.

The experimental data of [1] were generalized by the method of local modeling in the form of the dependence of the correction $\Psi_{s\varphi}$ to the standard law of heat exchange on the similarity parameter K_{pf} [3] expressing the influence of the distorting effect of the particles in the near-wall zone before their collision with the wall (influence of the primary effect of the particles) on the heat transfer. With the aid of the similarity parameter K_{pf} we were able to generalize the experimental data only for swirlers with angle of mounting the vanes φ_k = 15, 25, and 35°. For swirlers with φ_k = 45 and 60° it was impossible to generalize the experimental data on the basis of the similarity parameter K_{pf} because with large angles the secondary effect of the particles (after their collision with the wall) on the gas phase has a considerable influence on the heat exchange, and the similarity parameter K_{pf} does not take this influence into account.

The present article submits the results of generalizing the experimental data of [1] taking into account the influence of the secondary distorting effect of particles in the near-wall zone on the heat exchange, and a method is suggested for calculating the heat transfer of a swirled two-phase stream in a short channel.

In the subsequent analysis we will proceed from the following assumptions.

1. The process of heat transfer of two-phase swirled stream is the sum of the process of heat transfer of the carrier gas phase distorted by particles, and the process of heat exchange of the particles with the wall upon direct contact.

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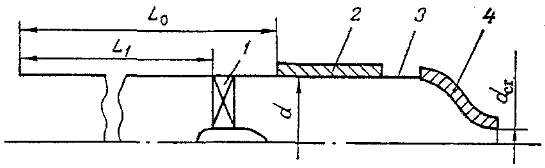

Fig. 1. Diagram of the unit of the experimental section: 1) swirler; 2) cylindrical experimental section; 3) adapter; 4) nozzle section.

2. Particles precipitated on account of inertia after collision with the wall are in a state of suspension, and in the near-wall zone they form the layer of suspended particles whose thickness is δ_{la}. In the examined section of this layer particles with different sizes move with the same mean speed. The axial component of this speed v_{la} is proportional to the axial component of the carrier medium w_x beyond the suspended layer ($v_{la} = a\, w_x$).

3. In case of gradientless flow, the local force of the aerodynamic effect of the particles of the suspended layer on the gas phase (force of the secondary effect) F_{ps} has the order of magnitude of the suspension force of the particles, i.e., of the force of gravity $F_{ps} = g\rho_{la}$.

In the examined section across the thickness of the suspended layer, the density of the particles ρ_{la}, and consequently also the aerodynamic force F_{ps} are taken to be constant.

The adopted model of the secondary aerodynamic effect of the particles enables us to write the integral equation of the impulses for the carrying gas phase of a swirled two-phase stream. This equation, in the projection onto the x axis, has the form

$$\frac{d}{dx}\int_0^R (p+\rho w_x^2)\, rdr = -R\tau_x + \int_0^R (F_{pj})_x\, rdr + \int_{R-\delta_{la}}^R (F_{ps})_x\, rdr, \tag{1}$$

where

$$\delta_{la} = \frac{1}{\rho_{la} v_{la}} \int_0^x g_{\text{in}}\, dx.$$

Taking into account the assumption that the force of the secondary effect of the particles F_{ps} across the thickness of the suspended layer is constant, we can transform the third term of the right-hand side of Eq. (1) into

$$\int_{R-\delta_{la}}^R (F_{ps})_x\, rdr \cong (F_{ps})_x R\delta_{la} = \frac{gR}{aw_x}\int_0^x g_{\text{in}}\, dx. \tag{2}$$

Analysis of Eq. (1) with a view to (2) by the methods of the similarity theory enables us to obtain the known similarity number K_{pf} [3] and the supplementary similarity number K_{ps} expressing the influence of the secondary distorting effect of the particles on the gas phase in the near-wall zone on the heat exchange:

$$K_{pf} = \frac{F_{pf} d_s}{\rho w^2}; \quad K_{ps} = \frac{\frac{g}{aw_x}}{\rho w^2}\int_0^x g_{\text{in}}\, dx. \tag{3}$$

Here

$$F_{pf} = -0.75\frac{c_D \rho_s}{d_s \rho_B}(|\vec{w} - \vec{w}_s|)^2.$$

Henceforth in the analysis, the proportionality factor *a* was taken to be equal to 0.5.

For a polydisperse gas suspension

$$K_{pf} = \frac{\Sigma (F_{pf})_i\, d_{si}}{\rho w^2}; \quad K_{ps} = \frac{\frac{2g}{w_x}}{\rho w^2}\Sigma\left(\int_0^x g_{\text{in}}\, dx\right)_i, \tag{4}$$

where d_{si} is the particle diameter of the i-th fraction.

The experimental data of [1] were generalized in the form of the dependence of the correction $\Psi_{s\varphi}$ to the standard law of heat exchange for a plate on the similarity numbers K_{pf}, K_{ps}:

$$\Psi_{s\varphi} = \frac{1}{\Psi_T \Psi_\varphi} \left(\frac{St}{St_0} \right)_{Re_T^{**}} = f(K_{pf},\ K_{ps}). \tag{5}$$

Here $St = \alpha_{sr}/c_p \rho_0 w_{x0}$; $\alpha_{sr} = \alpha - \Delta\alpha_{sk}$; $St_0 = 0.0128\, Re_T^{**\,-0.25} Pr^{-0.75}$; $\rho_0 w_{x0}$ is the maximum value of the axial component of the mass velocity of the gas in the near-wall zone, determined by the dependence [2]

$$\frac{\rho_0 w_{x0}}{\rho w_{av}} = [1 + 0{,}27\,(\mathrm{tg}\,\varphi_k)^{0.78}]\,(0{,}94 + 0.06\, m_k^2); \tag{6}$$

Re_T^{**} is the Reynolds number determined according to the nominal thickness of the energy loss δ_T^{**} and the viscosity of the gas phase at the wall temperature; Ψ_T is the correction to the standard law of heat exchange for a plate due to nonisothermy [4]:

$$\Psi_T = 4/\left(\sqrt{\frac{T_w}{T_i^*}} + 1 \right)^2; \tag{7}$$

Ψ_φ is the correction due to the swirling of the flow:

$$\Psi_\varphi = 1 + 1{,}08\,\Phi_{cs}^{0.67}, \tag{8}$$

where Φ_{cs} is the real value of the parameter of intensity of the swirling of the flow determined by the equation [2]:

$$\Phi_{cs} = 1{,}66\,(\mathrm{tg}\,\varphi_k)^{1{,}07}\,(d_{cb}/d)^{0{,}36}. \tag{9}$$

It should be pointed out that the dependence (8) for determining the correction Ψ_φ was obtained on the basis of the processed data on the heat transfer of a swirled single-phase flow of [2], taking into account the influence of the nonsimultaneous development of the dynamic and thermal boundary layers on the heat transfer under the conditions of a long heat-insulated passive section. This influence was taken into account by the experimental coefficient Ψ_{pa} whose numerical value is approximately equal to the correction Ψ determined according to the correlation for a nonswirled flow [4]:

$$\Psi_{pa} \cong \Psi = \left(\frac{L - L_0}{L} \right)^{0.086}. \tag{10}$$

Thus dependence (8) may be used for determining the correction Ψ_φ in a more general case (with any length of the passive section) but the influence of this section on the heat transfer must be taken into account with the aid of the correction Ψ_{pa}. The dependence for estimating Ψ_φ suggested in [2] may be used only when there is a heat-insulated passive section with a certain length [2].

The parameters of particle motion, the density of the mass inertia flows of particles to the wall g_{in}, needed for determining the similarity parameters K_{pf} and K_{ps}, were calculated by a numerical method on the assumption that the particles do not exert a reactive influence on the flow of the gas phase. For this we used the flow field of the carrying gas phase determined experimentally for all swirlers with the aid of a model experimental section [2] and a three-channel pressure sensor. The intensification of heat transfer $\Delta\alpha_{sk}$, due to contact heat exchange of inertially precipitated particles with the wall, was determined by a method explained in [4].

The results of the generalization of the experimental data of [1] with the use of the similarity parameters K_{pf} and K_{ps} are presented in Fig. 2, and the values of the points in Fig. 2 are given in Table 1. The experimental points are grouped fairly closely about the line determined by the relation

$$\Psi_{s\varphi} = (1 + 10^5 K_{pf})^{0.6}\,(1 + 6\cdot 10^4 K_{ps})^{0.25}. \tag{11}$$

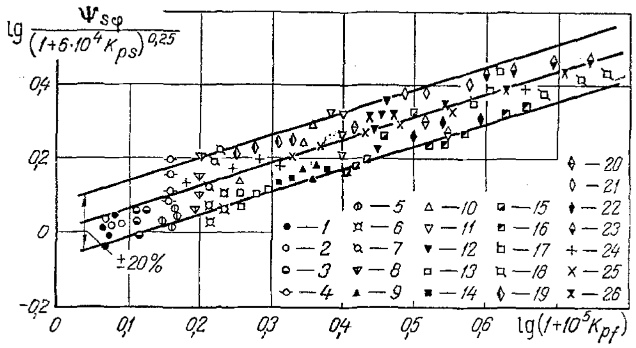

Fig. 2. Results of the generalization of the experimental data on the heat transfer of a swirled flow of gas suspension.

TABLE 1. Experimental Points of Fig. 2

Designation in drawing	φ_k	β	$Re\cdot10^{-5}$	Designation in drawing	φ_k	β	$Re\cdot10^{-5}$
1		0,249	0,86	14		0,322	1,16
2		0,256	1,65	15		0,513	1,55
3		0,329	1,14	16	35°	0,773	0,88
4	15°	0,518	2,08	17		0,872	1,42
5		0,529	0,92	18		1,155	0,88
6		0,825	0,83	19		0,291	2,11
7		0,870	1,48	20		0,531	0,88
8		0,259	1,61	21	45°	0,826	1,63
9		0,577	0,84	22		0,838	1,70
10	25°	0,603	1,16	23		1,129	0,94
11		0,690	2,15	24		0,267	0,84
12		0,924	1,42	25	60°	0,600	0,81
13	35°	0,236	0,91	26		0,920	0,75

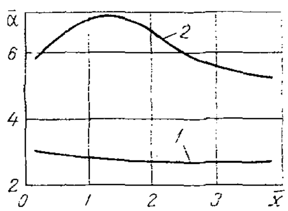

Fig. 3. Results of the calculation of the heat transfer of a swirled two-phase flow containing liquid aluminum oxide particles in a short channel: $1-\bar{\alpha}_{sr}=\frac{\alpha_{sr}}{\alpha_0}$; $2-\bar{\alpha}=\frac{\alpha_{sr}+\Delta\alpha_{sk}}{\alpha_0}$.

The similarity parameters K_{pf} and K_{ps} in the generalizing equation (11) express the influence on the heat transfer exerted by the aerodynamic action of the particles on the carrying gas phase in the near-wall zone before and after their collision with the wall. The numerical values of K_{pf} and K_{ps} are determined from the gas and particle parameters at a distance from the wall corresponding to $\bar{r} = r/R = 0.95$.

Equation (11) was obtained with changes of the determining parameters within the ranges $K_{pf} = (0.02-0.56)\cdot10^{-4}$; $K_{ps} = (0.14 - 21.10)\cdot10^{-4}$.

Thus the law of heat exchange for the gas phase of a swirled two-phase flow has the form

$$St = \frac{B}{2}\left(\frac{\eta_w}{\eta_{00}}\right)^m Re_T^{**-m} Pr^{-n} \Psi_T \Psi_\varphi \Psi_{s\varphi}. \quad (12)$$

If this equation is to be used for calculating heat transfer, it is necessary to solve the integral equation of energy for the carrying gas phase of a swirled two-phase flow which may be written in the form

$$\frac{d\,\mathrm{Re}_T^{**}}{d\bar{x}} + \frac{\mathrm{Re}_T^{**}}{\Delta T}\frac{d(\Delta T)}{d\bar{x}} = \mathrm{St}\cdot\mathrm{Re}_L + \frac{2}{\eta_{00}c_p\Delta T}\int_0^R Q_s r\,dr. \tag{13}$$

Here $\mathrm{Re}_L = 2R\rho_0 w_{x0}/\eta_{00}$; $\Delta T = T_f^* - T_w$; $\bar{x} = x/2R$; Q_s is the thermal effect of particles on 1 m^3 gas per unit time.

The second term on the right-hand side of Eq. (13) takes into account the thermal effect of the particles on the carrying gas phase. Since the change in temperature along the cylindrical part of the chamber is slight, the temperature lag of the particles and their thermal effect on the carrying phase are small and may be neglected. Taking this assumption into account and on the basis of the joint solution of Eqs. (12) and (13) we may write the following relationship for theoretically estimating the heat transfer of a swirled two-phase flow with arbitrary regularity of change of the wall temperature along the wall:

$$\mathrm{St} = \frac{\alpha_{s\Gamma}}{c_p\rho_0 w_{x0}} = \left(\Delta T\frac{\eta_w}{\eta_{00}}\right)^m \left[\frac{B}{2\,\mathrm{Pr}^n}\Psi_\varphi\Psi_{s\varphi}\right]^{\frac{1}{1+m}} \left[(1+m)\int_0^{\bar{x}} \mathrm{Re}_L\left(\frac{\eta_w}{\eta_{00}}\right)^m (\Delta T)^{1+m}\Psi_T\,d\bar{x}\right]^{-\frac{m}{1+m}}\Psi_T. \tag{14}$$

The constants B, m, n in (14) depend on the Reynolds number Re_T^{**} [4]. For $\mathrm{Re}_T^{**} < 10^4$ their values are 0.0256, 0.25, and 0.75, respectively.

By a method based on the use of Eqs. (6), (8), (11), and (14) we calculated the heat transfer of a swirled two-phase flow containing liquid particles of aluminum oxide in the cylindrical part of the model chamber (see Fig. 1). For the calculation we adopted the following initial data: pressure in the chamber p_k = 4 MPa, temperature T_k = 3350°K, wall thickness T_w = 2400°K, angle of swirling φ_k = 45°, size of the condensed particles d_s = 0.5-10 μm, mean flow-rate concentration of the particles at the entrance to the swirler β = 0.54. The intensification of heat transfer due to contact heat exchange of the particles with the wall was determined on the assumption that there is no splashing of the condensate upon impact interaction with a wall or film (there is no secondary distorting effect of the particles, K_{ps} = 0), and there is full energy exchange between the particles and the wall: $\Delta\alpha_{sk} = c_B g_{in}$.

The results of the calculation are presented in Fig. 3. It can be seen from this figure that because the swirled flow contains liquid particles, the heat-transfer coefficient is 6-7 times larger than the heat-transfer coefficient α_0 of an unswirled "pure" gas flow ($\varphi_k = \beta = 0$); this has to be taken into account in arranging heat protection of the chamber walls.

NOTATION

d = 2R, inner diameter of the cylindrical experimental section; d_{cb}, d_{cr}, diameter of the central body of the swirler and of the critical nozzle section, respectively; ρ_s, particle density; d_s, particle diameter; ρ_B, density of the substance of the particles; c_D) drag coefficient of the particles; φ_k, angle of setting of the swirler blades; L_0, length of the passive heat-insulated section; L, distance between the beginning of the heat-insulated pipe and the examined section; x, distance between the swirler and the examined section; p, c_p, ρ, pressure, specific heat, and density of the gas, respectively; w, w_x, gas speed and its axial component, respectively; w_s, speed of the particles; g_{in}, density of the mass inertia flow of particles to the wall; g, acceleration of gravity; F_{pf}, F_{ps}, forces of the primary and secondary aerodynamic effect of the particles, respectively, on 1 m^3 gas at the examined point; α, α_0, heat-transfer coefficients of two-phase and of pure gas flows, respectively; $\alpha_{s\Gamma}$, heat transfer coefficient of the carrying gas phase; $\Delta\alpha_{sk}$, intensification of heat transfer due to contact heat exchange of the particles with the wall; Ψ_T, Ψ_φ, $\Psi_{s\varphi}$, corrections for the standard law of heat exchange of particles made necessary by nonisothermy, swirling, and the presence of particles in the swirled flow; $\rho_0 w_{x0}$, maximum value of the axial component of the mass velocity of the gas in the examined section; η_w, η_{00}, dynamic viscosity of the gas at wall temperature T_w and stagnation temperature T_f^* respectively; Re_L, Reynolds number determined according to the maximum value of the axial component of the gas velocity w_{x0} in the examined section; $m_k = (d_{cr}/d)^2$, degree of partitioning.

LITERATURE CITED

1. F. I. Sharafutdinov, A. I. Mironov, V. A. Filin, and N. N. Koval'nogov, "Heat transfer of a swirled flow of gas suspension in the cylindrical part of a model chamber," in: Interuniversity Transactions. Heat and Mass Exchange in Aircraft Engines, Issue 2, KAI, Kazan (1979), pp. 96-100.

2. F. I. Sharafutdinov, A. I. Mironov, and V. K. Shchukin, "Effect of swirling of a flow on the heat transfer in the cylindrical part of the prenozzle space of a chamber," Inzh.-Fiz Zh., 36, No. 4, 595-601 (1979).
3. V. K. Shchukin, A. I. Mironov, V. A. Filin, and N. N. Koval'nogov, "Generalization of the experimental data on the heat transfer of a two-phase flow in the subcritical part of the nozzle," Izv. Vyssh. Uchebn. Zaved., Aviatsion. Tekh., No. 3, 121-126 (1978).
4. S. S. Kutateladze and A. I. Leont'ev, Heat and Mass Exchange and Friction in Turbulent Boundary Layers [in Russian], Énergiya, Moscow (1972).
5. V. K. Shchukin, A. I. Mironov, V. A. Filin, and N. N. Koval'nogov, "Heat exchange upon interaction of condensed particles with the wall," Inzh.-Fiz. Zh., 31, No. 3, 456-461 (1976).

EFFECT OF INITIAL VELOCITY DIFFERENCE BETWEEN PHASES ON EVOLUTION OF TWO-PHASE JET

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Results of an experimental study are presented concerning the effect which the initial difference between the velocity of the gas and the velocity of the pollutant particles have on the characteristics of an inundated air jet carrying a pollutant in the form of spherical particles of high-density material.

According to an earlier report [1], an experimental study of a turbulent air jet carrying heavy pollutants has demonstrated that, even when the velocity of the gas and the velocity of the pollutant particles are equal, there develops a difference of phase velocities (a flow nonuniformity) at the nozzle throat which then increases along the axis depending on the size and the concentration of particles. Laws governing the propagation of an air jet with heavy pollutants were further studied experimentally, to reveal the dependence of the jet characteristics on the initial difference of phase velocities. This experiment was also performed in the "model" format [1]. A two-phase mixture was formed with a nondisperse powder of spherical particles having a mean diameter of 45 μm (density of pollutant material 850 $kg{\cdot}sec^2/m^4$). Uniform profiles of gas velocity and pollutant velocity as well as of pollutant concentration in the nozzle throat were produced by means of a special shaping device [2] which, moreover, served as means of presetting the initial difference of phase velocities. These experiments were performed with the following initial differences between gas velocity and pollutant velocity: a) pollutant particles initially leading, their velocity being 35 m/sec and the gas velocity being 25 m/sec; b) pollutant particles initially lagging, their velocity being 35 m/sec and the gas velocity being 45 m/sec; c) velocity of pollutant particles and gas velocity initially equal, both 35 m/sec.

The pollutant concentration (ratio of pollutant to air on kg/kg basis) was, in all three cases, near unity.

The profiles of gas velocity and pollutant velocity as well as of relative pollutant concentration in cross sections of the jet up to 20 diameters away from the nozzle throat and r_0 = 15 mm in radius were in this experiment measured by the laser–optical method [3].

Electrocorundum particles smaller than 5 μm were in small quantities added as tracers for visually indicating the motion of the gaseous phase. The accuracy of measurements was within 5-7%.

Here are the results of this experiment.

The graph in Fig. 1 depicts the variation of the axial velocities of gas and particles for two values of the initial difference of phase velocities. Here U^0 is the mean velocity of gas or particles referred to the initial gas velocity and x^0 is the distance from the nozzle throat referred to the nozzle throat radius. Points 1 and 2 correspond to velocities of gas and particles in a flow with a high initial velocity of the gaseous phase. The graph indicates that at the given relation between phase velocities the relative difference between the axial velocities of particles and gas changes quite appreciably from positive to negative value. The velocities of the two phases also follow very different trends: the velocity of gas changes quite appreciably, while the velocity of particles changes only slightly and almost remains constant. In the other case of flow with a high initial velocity of particles, on the other hand, the velocities of gas and particles (points 3 and 4) vary so that their differences changes little and remains almost constant within the given range of distances from the nozzle

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