5. I. G. Kozhevnikov and L. A. Novitskii, Thermophysical Properties of Materials at Low Temperatures [in Russian], Moscow (1982), pp. 28-98.
6. A. Z. Volynets, A. V. Rozhdestvenskii, and Yu. M. Gavrilov, Inzh.-Fiz. Zh., 51, No. 6, 970-977 (1986).
7. B. P. Kamovnikov, G. V. Semenov, and N. D. Rozenshtein, Kholod. Tekhn., No. 1, 40-44 (1976).
8. G. V. Semenov, Investigation of Processes of Granulation and Sublimation Drying of Liquid and Pastelike Food Products [in Russian], Author's Summary of Dissertation for Kand. Tekh. Nauk, Moscow (1977).

TRANSVERSE TWO-PHASE FLOW AROUND A CYLINDRICAL HEAT EXCHANGE SURFACE

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Particle motion and deposition are modelled numerically on an infinite transversely streamlined cylinder subjected to force factors of a non-turbulent nature.

Considerable attention is expended in the literature on questions of the flow of a gas with particles around bodies. Many of them have been examined in application to problems of impurity filtration, motion of flying vehicles in clouds, and dynamics of atmospheric aerosols [1, 2].

Lately investigations of two-phase flow around obstacles are of great interest for thermal energy problems in connection with the utilization of low-grade solid fuels in boilers and the problems of contamination and erosive wear of convective heat transfer surfaces that occur here. The development of mathematical models of the flow of a gas with particles around heat exchange surfaces is needed to predict the contamination and wear. The approximation of a single particle is the simplest and sufficiently efficient approach when the particle motion is examined in a known field of gas parameters without taking account of the collective effects and reverse influence of the particles. But even in such a formulation two problems will occur, how to describe the motion of the continuous medium and what force factors to take into account in the particle motion equations? Only the aerodynamic drag f_a and gravity f_g forces were taken into account out of the whole set of factors in [3], while the particle motion equations were supplemented in [4] by expressions for the Safmen force f_S, the thermophoresis f_T and the migrational transfer under the action of the fluctuating gas velocity gradient. The viscous boundary layer is taken into account in both papers and the flow outside it is assumed potential. Viscous gas flow with solid particles around an infinite right cylinder was investigated in [5] with the reverse influence of the particles on the gas taken into account. The parameters of the continuous medium were computed in an Euler formulation while only the aerodynamic drag of the medium was taken into account in the Lagrange equations of particle motion.

The common disadvantage of the papers listed is taking incomplete account of the force factors in the particle deposition computations. For instance, there is no Magnus force f_M in the equations of motion in [3-5]. Meanwhile, particle gas suspensions in flows acquire substantial angular velocities (see [6]), consequently, it is impossible to neglect the Magnus force without sufficient foundations. Moreover, the temperature field needed to determine f_T was either not computed generally in these papers [5] or was calculated with the involvement of simplifying hypotheses that do not always have adequate foundations [3, 4].

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Results are presented in this paper of the construction of a mathematical model for viscous nonisothermal gas flow with particles around a cylinder with the Magnus, Safmen, thermophoresis, gravity, and aerodynamic drag forces of the medium taken into account.

Let us initially examine the problems of stationary laminar incompressible fluid flow around a circular cylinder. Taking into account the large quantity of published papers (see the survey in [7], say), this problem has long ago become a classic. Nevertheless, if it is assumed that the characteristics of separation flow around a circular cylinder should correspond to Kirchhoff–Helmholtz theory [8] for sufficiently high Reynolds numbers, then the Reynolds number Re = 280 [9] is substantially the limit to which the results obtained for the numerical solution can be considered reliable. In this connection, let us note that the fundamental difficulty in computing the flow around a circular cylinder is associated with modelling the wake when, in particular, an increase in the length of the circulation zone proportional to the number Re should follow from the model.

At the same time, as is shown in [7], the flow in the domain between the stream foward stagnation point and the separation point on the cylinder surface can be computed sufficiently exactly for significantly higher Reynolds numbers. The results of such a computation can be utilized as the basis for describing particle motion near the frontal zone of the cylinder surface.

Numerical investigation of the flow and heat transfer around a circular cylinder is executed within the framework of the stationary Navier-Stokes and energy equations written in natural variables in a polar coordinate system. The initial system of equations in divergent form, the difference approximation of these equations by a Leonard scheme of third-order accuracy, formulation of the boundary conditions and also the calculational procedure are described in detail in [7]. The computations are performed for the following values of the Reynolds number, defined according to the free stream velocity and the cylinder diameter: $Re = 10^2$, 10^3, and 10^4. The characteristic Prandtl number is chosen invariant and equal to $Pr = 0.73$. The mesh spacing of all the computational modifications equals $\pi/60$ in the tangential direction (the whole mesh includes 62×100 computational nodes). The fundamental computational results are presented in the table.

As is seen from the data represented, the flow and heat transfer at the frontal part of the cylinder surface are modelled satisfactorily in the whole range of computational Reynolds number, as satisfaction of the condition $Nu_F/Re^{0.5} \approx 1$ indicates in particular. The successful selection of the difference scheme that combines the directivity against the flow and the high order of the approximation contributes to this on one hand. On the other utilization of the method of local similarity [7], which does not permit development of the so-called flow pseudo-crisis, to determine the friction τ_w at the wall for $Re = 10^4$ contributes to this. At the same time, we have anomalous behavior of the flow and heat transfer parameters for $Re = 10^3$ and 10^4 in the wake behind the cylinder behind the stream separation point, the reasons for which are described in detail in [7]. In turn, this results in a small shift of the stream separation point to the rear stagnation point of the cylinder for $Re = 10^4$ ($\theta = 105.6°$ is obtained in [7] for the same number $Re = 10^4$ in the case of taking account of the turbulence mechanism with other conditions being equal), which, however, cannot strongly affect the quality of the numerical modelling of the flow and heat transfer near the frontal part of the cylinder surface. Therefore, since we are interested in particle deposition on a streamlined surface subjected to force factors (Magnus, Safmen, thermophoresis forces) many of which are substantial near the surface (see [6]), the obtained dynamic and thermal gas characteristics can be utilized to model the particle motion.

The descending particle motion around a horizontal cylindrical surface is described in a Cartesian coordinate system by the Lagrange equations

$$dU_p/d\tau = Ac_f D^{-1} W (U - U_p) - A\Omega (V - V_p) - (f_S - f_T)\cos\varphi + \mathrm{Fr}^{-1}; \tag{1}$$

$$dV_p/d\tau = Ac_f D^{-1} W (V - V_p) + A\Omega (U - U_p) + (f_S - f_T)\sin\varphi; \tag{2}$$

$$dX/d\tau = U_p; \quad dY/d\tau = V_p, \tag{3}$$

where $A = 0.75\rho^0$; f_S is the Safmen force, $f_S = 3.08\rho^0 D^{-0.5} Re_p^{-0.5} (U_\varphi - U_{\varphi p}) \times |dU_\varphi/dR|^{0.5}$; f_T is the thermophoresis force, $f_T = 8.6\rho^0 Re_p^{-2} \Lambda T_0^{-1}(dT/dR)$; $T_0 = tt_0^{-1}$; $W = \sqrt{(U - U_p)^2 + (V - V_p)^2}$; $R = \sqrt{X^2 + Y^2}$. The X axis is directed downward, and the origin

TABLE 1. Results of Computing the Flow around an Isolated Cylinder

Re	c_P	c_w	c_x	p_F	p_E	θ°	L	$\frac{\tau_w \sqrt{Re}}{2}$	Nu_F	Nu_E	Nu_m
1 ^{2}	0,786	0,283	1,070	0,528	—0,200	66,3	6,4	0,913	9,26	2,32	4,91
10^3	0,526	0,091	0,577	0,507	—0,042	101,3	10,0	0,833	32,22	8,83	13,62
10^4	0,410	0,012	0,422	0,502	0,081	101,5	8,4	0,830	95,50	46,02	45,10

agrees with the cylinder axis, $\varphi = \mathrm{arctg}\,|y/x|$. The first two components in the right sides of (1) and (2) take account of the drag of the medium for a stationary flow and the Magnus force, respectively, and the last component in (1) gravity.

The formulated mathematical model, including the gas velocity and temperature fields $(U_\varphi(R, \varphi), V_r(R, \varphi), T(R, \varphi))$, equations (1)-(3) and a number of auxiliary relationships (the dependences $c_f(Re_p)$, $\nu(t)$, $\rho(t)$, etc.), permits computation of the particle motion and deposition characteristics for a gas suspension flow around a cylindrical heat transfer surface. Values of the initial quantities selected for performing the computations were varied within the following limits: $\delta = 10...200$ μm, $t = 293...500$ K, $t_w = 293...500$ K, $d = 0.032$ m, $\rho_p = 1.65 \cdot 10^2 ... 1.65 \cdot 10^4$ kg/m³, $u_0 = 0.5...12$ m/sec. Values of the angular velocity were calculated from the relationship $\omega = u_0\delta^{-1}$. Estimates we made show that these values are in agreement with experimental data presented in the literature for the particle angular velocity in gas suspension flows. It was assumed in each computation that all the particles rotated in one direction while the quantity ω did not change during motion. Moreover, in order to determine the influence of f_M on the particle deposition characteristics, a number of computations was performed with the values $\omega = 0$ and $\omega = (10...100)u_0\delta^{-1}$. The working medium is air at atmospheric pressure with a density corresponding to the above-mentioned temperature range. The dependence of the deposition factor η on the Stokes number Stk was determined in the computations. Let us recall that the quantity η is the ratio between the number of deposited particles and their total number that could be deposited if they moved rectilinearly. For a uniform particle distribution far from the streamlined cylinder $\eta = (y_r - y_\ell)/d$, where y_ℓ, y_r are the left and right boundaries of the interval of ordinate values y such that the particles deposit for $y \in (y_\ell, y_r)$ and don't deposit for $y \in (y_\ell, y_r)$ on the cylinder. For definiteness we denote the particle trajectories corresponding to y_ℓ, y_r by the symbols ℓ and r, respectively. If the trajectories are symmetric with respect to the X axis, then $\eta = y_r/R$. The abscissa of the starting points was taken as $x_0 = -10.5d$ in all cases.

Certain results of the computation are represented in Fig. 1. It is seen from the figure that minimal Stk^{min} and maximal Stk^{max} Stokes numbers can be isolated provisionally on each curve, for which a bend is observed as a function of η(Stk). The probability of particle deposition for which $Stk < Stk^{min}$ is almost zero and almost one for $Stk > Stk^{max}$. As the number Re diminishes the values of Stk^{min} and Stk^{max} are shifted to the domain of smaller Stokes numbers.

There also follows from a comparison of the curves that in both isothermal and nonisothermal conditions the computed value of the deposition factor is elevated when taking account of all the force factors in the particle motion equations. The increase is especially substantial for small Reynolds numbers and intermediate values of the Stokes number between Stk^{min} and Stk^{max}. As the viscosity diminishes, i.e., as the Re number grows, the fraction of particles being deposited on the cylinder is reduced. Such a nature of the dependence η(Stk, Re) agrees qualitatively with the results presented in [1] for potential flow around a cylinder. An increase in the particle density results in growth of the deposition factor (curve 4 in Fig. 1) as should be expected. In the nonisothermal case for $t > t_w$ and other conditions being equal, the calculated values of the deposition factor are lowered (see Fig. 1b). A rise in the gas temperature should result in growth of the influence of the thermophoresis force f_T, i.e., an increase in η. Indeed, as our computations showed, the ratio $f'_T/f_T > 1$ and grows as t_w/t diminishes. Here f_T, f'_T are components of the thermophoresis force for the cases $t \approx t_w$ and $t \gg t_w$, respectively.

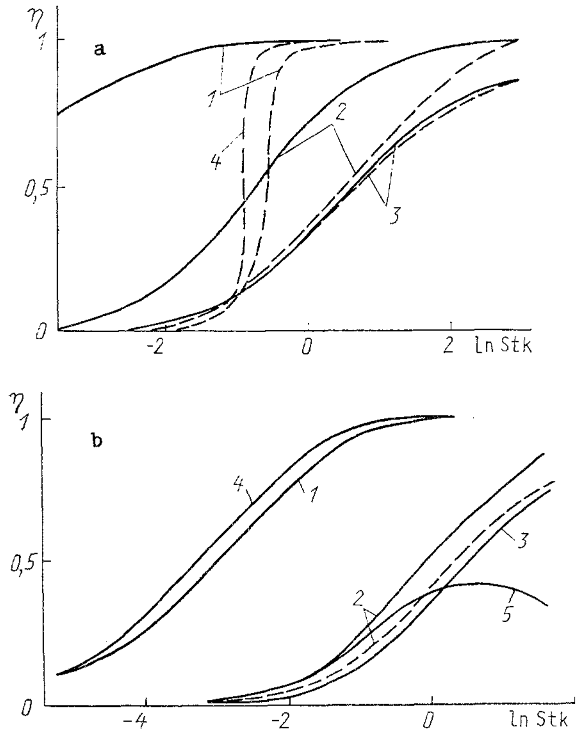

Fig. 1. The dependence $\eta(\text{Stk})$ with all the force factors (solid curves) and just f_a (dashed curves) in (1) and (2) for $t_0 = t = 300$ K (a) and $t_0 = 500$ K, $t = 293$ K (b): 1-3, 5) $\rho_p = 1600\ \text{kg/m}^3$; 4) $\rho_p = 16{,}000\ \text{kg/m}^3$; 1-4) $\omega = u_0\delta^{-1}$; 5) $\omega = 1.4\cdot 10^5\ \text{sec}^{-1}$; 1, 4) Re = 100; 2, 5) Re = 1000; 3) Re = 10^4.

However, as the gas temperature rises its viscosity increases, which requires the utilization of large values of the gas velocity in the computations for an invariant Re number. And for the same values of ν as under isothermal conditions this corresponds to large Reynolds numbers for which the deposition factor is smaller, as follows from Fig. 1a.

Computations showed that as the angular velocity grows to the values $\omega < u_0\delta^{-1}$ (we call them critical), the dependence $\eta(\text{Stk})$ is self-similar in ω. As the angular velocity increases further the self-similarity is spoiled and the dependence $\eta(\text{Stk})$ becomes nonmonotonic, the deposition factor is reduced for large Stokes numbers (curve 5 in Fig. 1b). Finally, such large values of ω in gas suspension flows are hardly real, however, the fact of the existence of an anomaly in the dependence $\eta(\text{Stk}, \omega)$ seems interesting to us.

Asymmetry in the particle flow around the cylindrical surface appears for large values of ω. If the location of the points y_ℓ, y_r depends only on the numbers Re and Stk for small angular velocities ($\omega \approx 0.5|du/dy|$), then as ω grows the particle trajectories will shift to the right. The influence of ω on particle motion is shown in Fig. 2. Despite the shifts of the ordinates y_ℓ and y_r the quantity η remains unchanged down to critical values of ω. The diminution in the deposition factor as ω increases further is associated with the fact that at such angular velocities the Magnus force component in (1) and (2) becomes greater than the remaining force factors. The direction of f_M depends on the sign of the difference $\Delta = u - u_p$ and its magnitude, on the absolute value of this difference. The trajectories ℓ in the right half-plane (see Fig. 2) have larger curvature than the trajectories r since they are nearer to the X axis where Δ is greater. Starting with a certain value $\omega^* > u_0\delta^{-1}$, the curvature of the trajectories ℓ grows abruptly while it is practically unchanged for the trajectories r. Consequently, for a particle with such an angular velocity to be deposited on the cylinder it is necessary to increase the value of y_ℓ substantially in the computations, which results in a drop in η. The quantity ω^* depends on the numbers Re and Stk as well as on the physical properties of the gas and particles. Its exact value has not been determined successfully in this paper. It is also seen from Fig. 2 that particle accumulation is possible in the root zone of the cylinder for large values of ω.

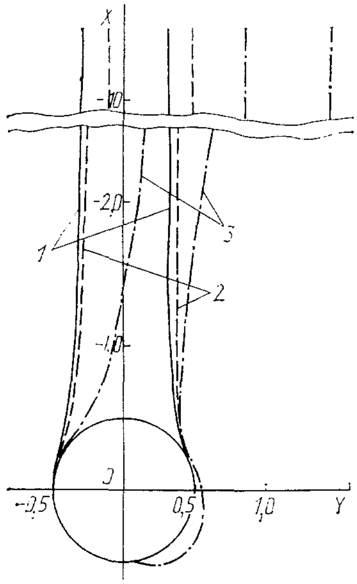

Fig. 2

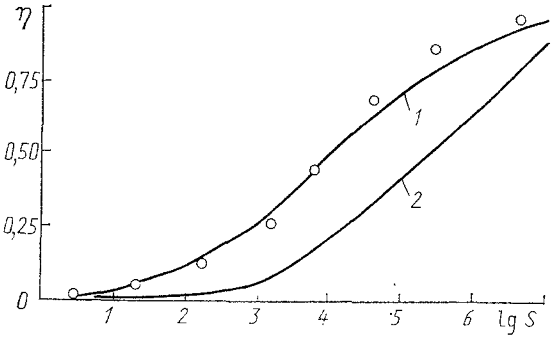

Fig. 3

Fig. 2. Particle limit trajectories as a function of their angular velocity for Re = 1000, Stk = 1.29: 1) $\omega = 0$; 2) $1.4\cdot10^4$ sec^{-1}; 3) $1.4\cdot10^5$ sec^{-1}.

Fig. 3. Comparison between computed values of the deposition factor and test data: 1) taking all force factors into account in (1) and (2); 2) taking account of just the aerodynamic drag force; points are test data [10].

Comparison of the results obtained with test data available in the literature, with [10], say, is of interest. The deposition factor of metallic and coal dust on a cylindrical surface covered by a vaseline layer was determined in this paper. The test data obtained were processes in the form of the dependence $\eta(S)$, where $S = 1.4\cdot10^3 Stk^{2.5} Fr Re^{0.5}$. Comparison of these data with the computation results, presented in Fig. 3, shows that when all the force factors are taken into account in (1) and (2) the calculated values of the deposition factor are in satisfactory agreement with tests. When taking just f_a into account in (1) and (2) a discrepancy is observed between the results being compared.

Therefore, the mathematical model developed permits describing the particle motion and deposition on a transversely streamlined cylindrical surface with satisfactory accuracy under both isothermal and nonisothermal conditions.

NOTATION

$U = uu_0^{-1}$, $V = vu_0^{-1}$, u, v are the longitudinal and transverse velocity components; $X = xd^{-1}$, $Y = yd^{-1}$; x, y are the longitudinal and transverse coordinates; $D = \delta d^{-1}$; $R = rd^{-1}$; d, δ are the cylinder and particle diameters, respectively; r is the running radius; $\Omega = \omega d u_0^{-1}$; ω is the angular velocity; $\tau = Tu_0 d^{-1}$; T is the time; C_w, C_p are the friction drag and pressure coefficients, respectively; C_x is the cylinder drag coefficient; c_f is the particle aerodynamic drag coefficient; L is the length of the circulation zone; θ is the angle of stream separation measured from the rear stagnation point; τ_w is the maximal friction on the wall; φ is an angle; P is pressure; $T = (t - t_w)/(t_0 - t_w)$; t is temperature; a is the thermal diffusivity coefficient; $\Lambda = \lambda/(2\lambda - \lambda_p)$; λ is the heat conduction coefficient; ν is the gas kinematic viscosity coefficient; $\rho^0 = \rho/\rho_p^{-1}$; ρ is the density; η is the deposition factor; g is free fall acceleration; $Fr = U_0^2/dg$ is the Froude number; $Nu = \alpha d/\lambda$ is the Nusselt number; $Pr = \nu a^{-1}$ is the Prandtl number; $Re = u_0 d\nu^{-1}$; $Re_p = u_0\cdot\delta\nu^{-1}$ is the Reynolds number; $Stk = u_0\rho_p\delta^2/(18\nu\rho d)$ is the Stokes number. Subscripts: E, F the quantity corresponds to the rear and forward stagnation points, respectively; m the mean value over the cylinder perimeter; 0 the quantity refers to the input section; p the quantity refers to particles; r the value of the quantity in the radial direction; w the value of the quantity on the cylinder surface; φ the value of the quantity in the tangential direction.

LITERATURE CITED

1. N. A. Fuks, Progress in the Mechanics of Aerosols [in Russian], Moscow (1961).
2. A. M. Mkhitaryan, Yu. V. Sukharnikov, and Yu. G. Koval', Aerodynamics [in Russian], No. 3, 19-30, Kiev (1977).
3. S. Yu. Belov, Yu. A. Rundygin, and B. V. Usik, Inzh.-Fiz. Zh., 43, No. 3, 499-500 (1982).
4. F. E. Spokoinyi and Z. R. Gorbis, Teplofiz. Vys. Temp., 19, No. 1, 182-199 (1981).
5. B. V. Whittle and V. Tabakov, Aerospace Engineering [Russian translation], No. 12, 50-57 (1987).
6. A. A. Shraiber, L. B. Gavin, V. A. Naumov, and V. P. Yatsenko, Turbulent Flows of Suspensions [in Russian], Kiev (1987).
7. I. A. Belov and N. A. Kudryavtsev, Heat Elimination and Drag of Pipe Packets [in Russian], Leningrad (1987).
8. V. V. Sychev, A. I. Ruban, Vik. V. Sychev, and G. L. Korolev, Asymptotic Theory of Separation Flows [in Russian] (V. V. Sychev, ed.), Moscow (1987).
9. B. Fornberg, J. Fluid Mech., 98, Pt. 4, 819-855 (1980).
10. V. I. Ignat'ev and N. I. Zverev, Teploenergetika, No. 3, 36-40 (1958).

THERMAL PROPERTIES OF SUPERHEATED POTASSIUM VAPOR AT TEMPERATURES TO 2150 K AND PRESSURES TO 10 MPa.

1. AN EXPERIMENTAL INVESTIGATION OF THE THERMAL PROPERTIES

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Data have been obtained for the PvT relationship of superheated potassium vapor over ranges of the parameters of state not previously investigated; a modified constant-volume piezometric method has been used with an error not exceeding 1%.

The scanty experimental work on the investigation of the thermal properties of potassium in the gaseous phase [1-5] was carried out mainly in the U.S.A. in the middle 1960s (see Table 1). A critical evaluation of each of these studies is given in [6], and conclusions are drawn as to the accuracy of the experimental data based on a graphical analysis and comparison of the interconsistency. As a result of this analysis paper [2] was taken to be the most accurate investigation while the data of [1] and [5] had the largest errors. For making thermodynamic generalizations experimental data are necessary which have high dependability and sufficient measurement accuracy. Such investigations include papers [2] and [3], the experimental data of which provide a mass of experimental points which are suitable for thermodynamic generalization.

However, as can be seen from Table 1 these data were obtained over limited ranges of the state parameters. The authors of references [2-4] who used in their investigations the method of constant-volume piezometry with a zero-membrane in the hot zone were not able to carry out measurements at high values of the parameters. Tests show that a membrane placed in the hot zone operates unreliably, deforms, and shifts its zero position. In order to describe the thermodynamic properties of potassium vapor over a wide range of the parameters of state additional experimental investigations are required at high temperatures and pressures. In this connection, a method of constant-volume piezometry with the zero-membrane in the cold zone has been developed in the MAI [Sergo Ordzhonikidze Aviation Institute, Moscow] for the measurement of the specific volumes of metal vapors [7].

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