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CHARACTERISTICS OF CENTRIFUGAL SEPARATOR

Yu. M. Grishin, V. M. Kozlov, and A. A. Mosin

UDC 621.039.524+532.517

An approximate method is proposed for the calculation of the integral separational characteristics of a centrifugal separator.

The process of separating two-phase (two-component) mixtures forms the basis of many production technologies [1]. One of the possible models for calculating the separational characteristics of a centrifugal separator (CS) of the standard scheme shown in Fig. 1 is considered in the present work. It has been established experimentally [2] that, in the central part of the separation zone (SZ), there arises an axial column of carrier gas that is practically free from inclusions of the second phases; "particles" of gas in the region of the boundaries of this column move around the axis of the system at some angular velocity. The main simplification of the model proposed is that the axial column of carrier gas is represented as a rigid impermeable cylinder with a radius R_2 that is constant over the SZ height. Flow of the mixture under the action of the applied pressure difference is then considered in a channel bounded by two coaxial cylinders of radii R_1 and R_2; the inner cylinder, modeling the axial column of carrier gas, moves in the axial direction at a velocity U_0 and rotates about its axis at constant angular velocity ω. It is assumed that the phase which is to be separated is present, and moves, in the form of undeformable, indivisible spherical particles. In addition, only the region of "dilute" mixtures, with $nR_1a^2 \ll 1$, is considered; in the first approximation, according to [3], this allows: a) the influence of collisions between particles on the overall character of the disperse-phase motion to be neglected; b) the assumption to be made that the presence of particles has no influence on the velocity-field distribution of the carrier gas. Note here that satisfying the condition of a "dilute" mixture imposes sufficiently rigorous constraints on the magnitude of the mass content of particles in the flow at the SZ inlet, b_0. Thus, for example, estimation of the limiting value of b_0 for a mixture of air (carrier gas) and water (disperse phase) gives (taking into account that $\varkappa b_0 \sim na^3$)

$$b_0 \ll \left(\frac{\bar{a}}{R_1}\,\frac{\rho'}{\rho}\right) \sim \frac{10\sigma}{\rho w_*^2}\,\frac{1}{\varkappa R_1} \sim 20\%. \tag{1}$$

Within the framework of the given model, the velocity distribution of the carrier-gas flow **w** is determined from the solution of the steady equations of motion of a single-phase incompressible medium [4] between two coaxial cylinders (the effect of spatial variation of the flow density may be neglected in view of the smallness of the carrier-gas characteristic velocity in the SZ $w_* = 10-30$ m/sec in comparison with the velocity of sound). In this system, the cylinders are regarded as infinitely extended in the axial direction, so that edge effects

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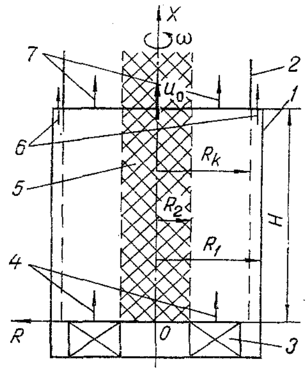

Fig. 1

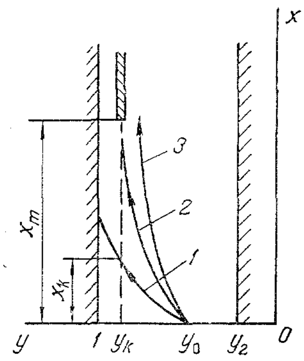

Fig. 2

Fig. 1. Diagram of centrifugal separator: 1) body; 2) central channel; 3) eddy generator; 4) mixture inlet into separation zone; 5) "central cylinder"; 6) removal of separated disperse phase; 7) discharge of mixture from the SZ.

Fig. 2. Particle trajectories in the SZ channel: 1) $\beta < \beta_{cr}$, particles falls in the separated-phase zone; 2) $\beta = \beta_{cr}$; 3) $\beta > \beta_{cr}$, particle is not separated in the SZ.

may be ignored. The solution is found for the case of small variation in the gas-flow velocity in the section of the SZ in the axial direction, i.e., when $(H/w)(\partial w/dX) \ll 1$ and in the first approximation it may be assumed that $w \neq w(X)$. Note that, in view of this assumption, no account is taken, in the given model, of the decrease in kinetic energy of the carrier gas caused in real conditions by energy dissipation with increasing distance of the flow from the eddy generator, and hence constraints on the magnitude of the maximum extent of the SZ, in accordance with the above inequality, must be introduced in the given model. Taking account of the axial symmetry of the problem $(\partial/\partial\varphi = 0)$, the following expressions are obtained (in dimensionless form) for the components of the gas-flow velocity in a cylindrical coordinate system

$$W_R = 0,\ W_\varphi = C_2\left(\frac{1}{y} - y\right),$$
$$W_x = \alpha W_{x1}(y) + \gamma W_{x2}(y), \tag{2}$$

where

$$W = w/w_*;\ W_{x1} = (\ln y)/\ln y_2;\ W_{x2} = 1 - y^2 + C_1 \ln y;\ y = R/R_1;$$
$$C_1 = (y_2^2 - 1)/\ln y_2;\ C_2 = y_2/(1 - y_2^2);\ y_2 = R_2/R_1;\ \alpha = U_0/\omega R_1;$$
$$\gamma = 0{,}25\, CM^2\mathrm{Re};\ \mathrm{Re} = R_1 w_*/\nu;\ M^2 = P_*/\rho w_*^2;$$
$$C = \left[1 - \alpha \int_{y_2}^{1} y W_{x1}(y)\, dy\right] \Big/ \left[4M^2\,\mathrm{Re} \int_{y_2}^{1} y W_{x2}(y)\, dy\right];\ w_* = G/2\pi R_1^2\rho.$$

In view of the assumption that the mixture is "dilute," the motion of the set of disperse-phase particles may be analyzed on the basis of investigating the motion of an arbitrary particle. As shown by estimating the individual components of the forces acting on a particle in the gas flow [5], it is sufficient, in most cases that are of practical interest, to take account only of drag forces of Stokes type; this is valid when the inequality $\mathrm{Re_p} = \bar{a}\mathrm{Re}/R_1 \lesssim 1$ is satisfied. Estimates of $\mathrm{Re_p}$ for the range of variation of the basic parameters of the system relevant to the experiment of [2, 6] show that $\mathrm{Re_p} \lesssim 10$, and hence application of the Stokes law is formally invalid. Taking into account [7]: 1) that there are essentially no rigorously well-founded relations for the drag coefficient of the particle C_p in the region $\mathrm{Re_p} \in [1, 10]$; and 2) that the value of C_p when $\mathrm{Re_p} \in [1, 10]$ is not greatly

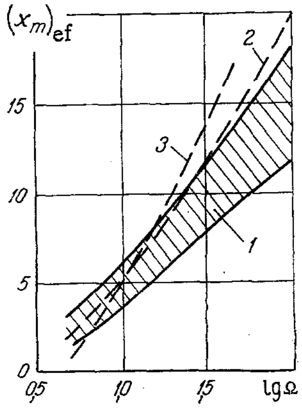

Fig. 3. Influence of angle of swirl of flow Ω on the effective length of the separation zone $(x_m)_{ef}$: 1) experiment [2]; 2) curve calculated for the variant $\gamma = 0$; 3) curve calculated for the variant $\alpha = 0$.

different from the values of C_p calculated in this range of Re_p from the Stokes law, while analytic description of particle motion using a non-Stokes law is extremely complicated, it is reasonable to restrict consideration to a semiquantitative analysis of particle motion in the given model of the process over the whole of the range $Re_p \leqslant 10$ by the Stokes law. In this case, the projection of the equation of motion takes, taking Eq. (2) into account, the dimensionless form

$$\frac{d^2\varphi}{dt^2} = -\frac{2}{y}\frac{dy}{dt}\frac{d\varphi}{dt} - \beta\frac{d\varphi}{dt} + \beta C_2\left(\frac{1}{y^2} - 1\right),$$
$$\frac{d^2y}{dt^2} = y\left(\frac{d\varphi}{dt}\right)^2 - \beta\frac{dy}{dt}, \tag{3}$$
$$\frac{d^2x}{dt^2} = -\beta\frac{dx}{dt} + \beta\left[\gamma(1 - y^2 + C_1\ln y) + \alpha\frac{\ln y}{\ln y_2}\right],$$

where $\beta = 18R_1^2\varkappa/(a^2 Re)$. The initial conditions for Eq. (3) are

$$t = 0,\ \varphi = 0,\ y = y_0 \in [y_2,\ y_k],$$
$$x = 0,\ \frac{d\varphi}{dt} = K_\varphi C_2\frac{1 - y_0^2}{y_0^2};\ \frac{dy}{dt} = 0,\ \frac{dx}{dt} = K_x[\alpha W_{x1}(y_0) + \gamma W_{x2}(y_0)].$$

Here K_x, K_φ are the coefficients of particle slip with respect to the gas velocity at the SZ inlet for the x and φ component of the particle velocity, respectively. As shown by subsequent calculations, variation in $K_{x,\varphi}$ in the range 0.6-1.4 has practically no effect on the final results, so that $K_{x,\varphi} = 1$ is assumed below. This is because: a) as a result of interactions with the gas flow, the particles take on a velocity close to the gas velocity, "partially losing information" on its initial velocity [8]; b) the calculated value of the separational characteristic η is the ratio of the mass flow rates of disperse phase (see below), each of which depends approximately identically on K.

The assumptions on which the model rests impose sufficiently rigid constraints on the range of variation of the basic system parameters (the mass content and particle size, etc.).

It may be shown from Eq. (3) that, for fixed values of $x_m = H/R_1$, y_0, α, γ, there always exists a value β_{cr} such that no particles with $\beta \geq \beta_{cr}$ reach the coordinate y_k for $x \in [0, x_m]$ (i.e., no particles are separated), and hence the particles all leave the SZ in the mixture discharged through the central channel* (Fig. 2); the functional relation of β_{cr} with the other parameters takes the form

$$x_m = \alpha\tilde{x}_{k1}(\beta_{cr},\ y_0) + \gamma\tilde{x}_{k2}(\beta_{cr},\ y_0),$$

where $\tilde{x}_{ki}$ is the axial coordinate of the separated particle, $\tilde{x}_{ki} \in [0, x_m]$. The dependence $\tilde{x}_{ki}(\beta_{cr}, y_0)$ is found by numerical solution of Eq. (3): $\tilde{x}_{k1}$ for the case $\gamma = 0$, $\alpha = 1$; $\tilde{x}_{k2}$ for $\gamma = 1$, $\alpha = 0$.

Analysis of the results shows that, for the range of variation of the basic SZ parameters that is of practical interest, the function $\tilde{x}_{ki}(\beta)$ is almost linear and β_{cr} may be calculated from the following interpolational relations:

*The model takes no account of processes of departure (breakaway) of particles from the zone of separated phase $y \in [y_k, 1]$. This imposes a constraint on the magnitude of the carrier-gas flow velocity, which must not exceed some critical value [6].

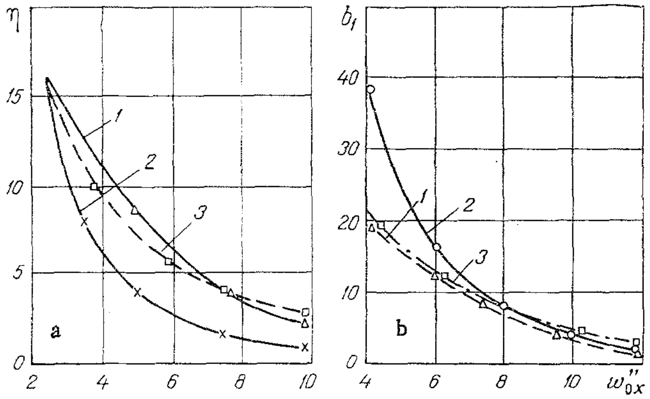

Fig. 4. Dependence of the separation characteristic η(%) (a) and the mass content of particles at the SZ inlet b_1 (%) on w''_{0x} (m/sec): 1) experiment [7]; 2) theory with $a_* =$ const; 3) theory with $a_* = a_{*0}(w''_{0x})^{-0.25}$ and $a_{*0} =$ const.

for $y_0 \in [y_2, y']$

$$\beta_{cr} = \left(\sum_{i=1}^{2} \frac{\beta_{cr\,i}}{\beta_{cr\,i} - B_i} - 1 \right) / \sum_{i=1}^{2} \frac{1}{\beta_{cr\,i} - B_i}, \tag{4}$$

for $y_0 \in [y', y_k]$

$$\beta_{cr} = \frac{\alpha\gamma}{\alpha + (2 - C_1)\gamma \ln y_2} \left[\frac{-4C_2^2 \ln y_2}{\ln\left(\frac{1 - y_0}{1 - y_k}\right)} \right].$$

Here y' divides the whole range $y_0 \in [y_2, y_k]$ into two parts in which Eq. (4) is valid; y' is close to y_2, and depends weakly on y_2 (as shown by calculation, $y' = 0.7$–0.8);

$$\beta_{cr1} = B_1 + A_1 x_m/\alpha,\ \beta_{cr2} = B_2 + A_2 x_m/\gamma,\ B_1 \simeq 2(1 - 2y_2),$$
$$B_2 \simeq 3(1 - 2y_2),\ A_1 \simeq 4y_2 - 1,\ A_2 \simeq 10{,}2y_2 - 3{,}1.$$

Knowing the dependence for β_{cr}, one of the most important integral parameters of the SZ may be determined: the separational characteristic η, which is understood to be the ratio of the mass flow rate of disperse phase through the central channel at the SZ exit, G_1', to the mass flow rate of disperse phase at the SZ inlet, G_0': $\eta = G_1'/G_0'$. The distribution function of particles with respect to diameter at the SZ inlet, $f(a, y_0)$, is now introduced, in such a way that $f da$ defines the proportion of particles with a diameter in the range from a to $a + da$ in unit volume of gas with coordinate y_0 (the normalization is $\int_0^\infty f da = 1$). For the mass flow rate of particles with a diameter in the range from 0 to a at the SZ inlet, the following expression may be written

$$G'(a) = G_* \int_{y_2}^{1} y_0 W_x(y_0)\, n(y_0)\, \psi(a, y_0)\, dy_0,$$

where

$$G_* = \pi^2 \rho' R_1^2 w_* \bar{n}/3;\ n(y_0) = \tilde{n}(y_0)/\bar{n};\ \psi(a, y_0) = \int_0^a a^3 f(a, y_0)\, da.$$

Then, the total mass flow rate of particles $G_0' = G'(a_m)$, where a_m is the maximum diameter of particles with the given distribution. Numerically, G_1' is equal to the mass flow rate of particles at the SZ inlet with diameters in the range $[0, a_{cr}]$, i.e., $G_1' = G'(a)$, where $a_{cr} = (18\varkappa R_1^2/\mathrm{Re}\beta_{cr})^{1/2}$.

Thus, $\eta = G'(a_{cr})/G'(a_m)$. To obtain specific dependences for η, it is necessary to know the form of the functions $n(y_0)$ and $f(a, y_0)$. It is possible to proceed in two ways here: 1) to establish these dependences from experiment; 2) to specify the form of f and n and compare the result obtained for η with experiment. The second option will be taken here, and the following case will be considered as an example: the concentration of disperse-phase particles is uniformly distributed in the inlet cross section $n(y_0) = 1$, and $f(a)$ takes the form

$$f(a) = (a/a_*^2)\exp(-a/a_*),$$

where a_* is the most probable particle diameter, and $a_* \neq a_*(y_0)$. This form of the dependence $f(a)$ is chosen from considerations of the most satisfactory agreement of the calculated value of η with the known experimental data. In this case, taking account of Eq. (4) and the condition that $a_m \to \infty$, η is determined from the approximate relation

$$\eta(z) \simeq 1 - \Phi(z), \tag{5}$$

where

$$\Phi(z) = \sum_{m=0}^{3}(z^m/m!)\exp(-z),\ z = \frac{6F}{\sqrt{1-y_2^2}}\left(\frac{\nu\varkappa R_1}{w''_{0x}a_*^2}\right)^{1/2};$$

$$F = \left[\left(\sum_{i=1}^{2}\frac{1}{\beta_{cr\,i}-B_i}\right)\Big/\left(\sum_{i=1}^{2}\frac{\beta_{cr\,i}}{\beta_{cr\,i}-B_i}-1\right)\right]^{1/2};$$

$w''_{0x} = G/\pi\rho R_1^2(1 - y_2^2)$ is the mean (over the flow rate) of the carrier-gas velocity in the axial direction.

Expressions for η in the two limiting cases of the proposed model of the process follow obviously from Eq. (5): 1) the case when $\gamma = 0$, $\alpha \neq 0$, axial motion of the gas occurs only as a result of axial displacement of the "central cylinder"; 2) $\alpha = 0$, $\gamma \neq 0$, axial motion of the gas is the result of the action of the pressure difference applied at the separation length H with a motionless ($u_0 = 0$ but $\omega \neq 0$) "central cylinder."

In character, the dependence $\eta(z)$ is such that, for $z \gtrsim 10$, η is close to unity, so that the inequality $z \gtrsim 10$ defines the range of variation of the SZ parameters with unsatisfactory phase separation. When $z \lesssim 1$-2, η is close to zero ($\eta \lesssim 6\%$) and effective separation occurs; $\eta(z)$ may be calculated in this case from the formula

$$\eta(z) = \sum_{k=1}^{\infty}\frac{1}{k!}\left(\frac{d^k\eta}{dz^k}\right)\Big|_{z=0} z^k \simeq z^4/4!$$

For the two limiting cases above, the model of the limiting relation between the SZ parameters with effective phase separation ($\eta \simeq 5\%$) takes the form (for $y_2 = 1/3$)

$$\frac{\nu\varkappa R_1}{a_*^2 w''_{0x}}\,\frac{\mathrm{tg}\,\Omega}{1+K_i x_m/\mathrm{tg}\,\Omega} \simeq 0{,}1, \tag{6}$$

where K_i is a numerical factor; the subscript i indicates the limiting variant of the model: when $i = 1$, $\gamma = 0$; when $i = 2$, $\alpha = 0$; $K_1 = 0.5$; $K_2 = 0.126$. In this case $\tan\Omega = w''_{0x}/w''_{0\varphi}$ is the tangent of the angle of swirl of the flow in the SZ inlet cross section, where $w''_{0\varphi}$ is the mean (over the flow rate) of the gas-flow velocity in the azimuthal direction, and

$$w''_{0\varphi} = \frac{w_* C_2}{1-y_2}\int_{y_2}^{1}\left(\frac{1}{y} - y\right)dy.$$

Note than $\tan\Omega \simeq d$ for the first limiting variant ($\gamma = 0$), and $\tan\Omega \simeq \gamma$ for the second.

In Fig. 3, curves of $(x_m)_{ef}$ against $\tan\Omega$ are shown for SZ with effective phase separation, as calculated from Eq. (6) for the two limiting variants of the model and as experimentally established for an air—water mixture [2]. Significant disagreement of the results of calculation and experiment is observed only in the region $x_m \gtrsim 10$, which is primarily associated with the neglect, in the given model, of effects of kinetic-energy dissipation for the flow with increasing distance from the eddy generator. Hence, the value $x_m \simeq 10$ is the upper limit on the applicability of the model. Note that calculations for the first limiting variant ($\gamma = 0$) are in better agreement with experiment [2].

The qualitative influence of individual SZ parameters on η is evident from Eq. (5) and is satisfactorily in agreement with experimental data [2, 6]. As an example of quantitative comparison, curves of η as a function of w_{0x}'', calculated from Eq. (5) (variant $\gamma = 0$) with $a_* = \text{const}$ and the experimental dependence are shown in Fig. 4a.

The mass content of disperse particles at the exit from the SZ in the flow passing through the central channel is defined as

$$b_1 \simeq G_1'/(G + G_1') = \eta/(\eta + \varkappa w_{0x}''/w_{0x}'),$$

where $w_{0x}' = G_0'/\pi\rho' R_1^2(1 - y_2^2)$ is the mean (over the flow rate) reduced velocity of the disperse phase at the SZ inlet. In Fig. 4b, calculated and experimental [6] curves of b_1 as a function of w_{0x}'' are shown. The results of the comparison indicate fairly significant discrepancy of the curves in the region of small w_{0x}'' (for $w_{0x}'' \leqslant w_{0x}'$), which is associated with violation of the conditions of "operation" of the calculation model in Eq. (1): the amount of disperse phase with $w_{0x}''/w_{0x}' \leqslant 1$ is so large ($b_0 \sim w_{0x}'/w_{0x}''$) that it is already impossible to neglect the influence of the presence of this phase in the mixture on the carrier-gas velocity field and it is also inappropriate to represent this phase as a disperse component.

The calculation model outlined above is semiempirical, since it rests on the introduction of quantities and dependences that are not known a priori but must generally speaking be determined from experiment: this refers to the form of the functions $f(a, y_0)$, $n(y_0)$ and the quantity y_2.† The results obtained using this model may be improved by means of changes in form of the distribution function and the profile of the particle concentration at the SZ inlet. For the form of these functions considered in the present work, more accurate results may be obtained if the most probable particle diameter a_* is not understood to mean some fixed value determined from the "reference" point of a specific experiment, but rather a_* is represented, on the basis of the known experimental data, as a function of the basic physical parameters of the mixture.

For example, if $a_* = a_{*0}(w_{0x}'')^{-0.25}$, where $a_{*0} = \text{const}$, then the calculated curves of η and b_1 shown in Fig. 5 are in significantly better agreement with experiment, even at small values $w_{0x}'' \sim w_{0x}'$.

The results of calculating the separational characteristics of the SZ are in completely satisfactory agreement with experimental data in the following range of variation of the geometric and physical parameters of the system: $b_0 \leqslant 20\%$, $(H/R_1) \leqslant 10$, $w_{0x}'' \simeq 2\text{-}12$ [m/sec]. Hence, the method of SZ calculation outlined here, despite the fairly sweeping assumptions on which it is based, may be regarded as the first approximation in developing more rigorous methods.

NOTATION

R_1, R_2, radii of SZ body and "central cylinder"; H, extent of SZ; U_0, ω, axial and angular velocity of "central cylinder"; $y = R/R_1$, $x = X/R_1$, φ, dimensionless coordinates; σ, surface tension of water; ν, kinematic viscosity of carrier gas; $\mathbf{w}$, velocity vector of gas flow; $W = w/w_*$, dimensionless velocity vector of gas; w_*, characteristic velocity; w_0'', w_0', mean (over the flow rate) reduced velocities of the gas and disperse phase, respectively, in the SZ inlet cross section; G, G', mass flow rate of gas and disperse phase; $\bar{n}$, $\tilde{n}$, mean and actual concentration of disperse-phase particles; a, $\bar{a}$, a_{cr}, a_*, actual, mean, critical, and most probable diameter, respectively, or disperse-phase particles; $f(a)$, distribution function of particles with respect to the diameter; $\varkappa = \rho/\rho'$, ratio of gas-flow density ρ to the density of the disperse-component material ρ'; b_0, mass content of particles in the mixture at the SZ inlet; η, separational characteristic of SZ; Ω, angle of swirl of flow at the SZ inlet.

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†In the given estimates, y_2 must be understood to denote, as shown by comparison with experiment, the ratio of the radius of the central core of the eddy generator to the radius of the SZ body.

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CONVECTIVE HEAT AND MASS TRANSFER OF REACTING PARTICLES AT LOW PECLET NUMBERS

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UDC 532.72

The problem of convective diffusion to a spherical particle in a gas is solved under the condition that the surface chemical reaction rate depends on the reagent concentration near the surface.

The first five terms of the asymptotic expansion in the low Peclet number have been obtained for the medium Sherwood number. Certain specific cases of the surface reaction have been analyzed.

At low Peclet numbers the problem of heat and mass transfer of a solid sphere around which a stationary Stokes stream flows, was first investigated by the method of joined asymptotic expansions in [1]. Constancy of the concentration was assumed far from the particle and on its surface. For the medium Sherwood number the first five terms of the asymptotic expansion were obtained. The extension of this problem to the case of a particle of arbitrary shape was made in [2], where a three-term expansion in the Peclet number was obtained for the medium Sherwood number. An analogous problem was considered in [3, 4] for a sphere, where expressions [5] obtained by the method of joined asymptotic expansions in the low Peclet number were utilized for the fluid velocity field, Convective diffusion to a sphere and particle of arbitrary shape around which a homogeneous translational stream flows during the progress of an isothermal reaction of the first kind on its surface was examined in [6, 7]. The mass transfer of a sphere during the progress of a chemical reaction of the first and second orders on its surface is investigated in [8]. The problem with arbitrary surface reaction kinetics was considered in [9] in the case of Stokes flow around the sphere.

It is assumed that the Reynolds number $R = aU/\nu$ and Peclet number $P = aU/D$ are small (for a gas the Schmidt number is $Sc = \nu/D = O(1)$. A chemical reaction with a finite reaction rate $F(c^*)$ proceeds on the particle surface where the function F is governed by a heterogeneous reaction mechanism. Thus, for a reaction of order $\varkappa$ $F = ka^{-1}c_\infty D(c^*/c_\infty)^\varkappa$.

The process of reagent transport is determined by the convective diffusion equation and the boundary conditions which have the following form in dimensionless variables in a spherical r, θ coordinate system coupled to the particle:

$$\frac{P}{r^2}\frac{\partial(\psi,\, c)}{\partial(r,\, \mu)} = \Delta c, \quad c = \frac{c_\infty - c^*}{c_\infty}, \quad \mu = \cos\theta, \tag{1}$$

$$r \to \infty, \quad c \to 0; \quad r = 1, \quad \partial c/\partial r = f(c), \quad f(c) \equiv -a(c_\infty D)^{-1} F(c^*). \tag{2}$$

Here a and U are selected as the scales of the dimensionless quantities.

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