DETERMINATION OF THE BOUNDARY TEMPERATURES AND DIMENSIONS OF THE EVAPORATING ZONE IN A SPRAY DRYING APPARATUS WITH HEAT SUPPLY FROM THE HIGH-TEMPERATURE WALLS

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The heat exchange of a wall of an apparatus with turbulent flow of an absorbing medium is examined. As a result of the treatment of experimental data dimensionless relationships are obtained for determining the length of the nonevaporating part of the torch and the average temperature of the vapor–gas medium at the end of the evaporation zone.

The possibility of combined drying and calcination of the dry residue in a single apparatus, the high intensity of the processes, and the minimum discharge of waste gases into the atmosphere are characteristic of atomizing tubular driers with heat supply from the walls. In connection with the future prospect of introducing driers of this kind into industry it has appeared necessary to study the special features of the heat and mass exchange in these apparatus.

The temperature fields of the moving screened thermocouple are measured in the vertical direct flow apparatus with a diameter of 300 mm and length of 2000 mm. The heating of the wall of the apparatus is carried out by a power transformer with low voltage currents. The boundaries of the evaporation of the atomized water were determined from the deposition of solid salts on the experimental rod which was installed in the lateral cross section of the apparatus at various distances from the nozzle of the pneumatic jet. The average discharge of liquid varied from 10-25 dm^3/h, the average specific discharge of the atomizing air varied from 0.5-1.0 kg/kg. The temperature of the wall was established in the region of 400 to 900°C.

The special features of the method of investigating the heat exchange and the boundaries of evaporation of the torch of atomized water have been examined previously [1, 2].

In expressing the process the basis adopted was the mathematical model proposed by F. N. Shorin [3] for solving the inverse problem of heat exchange, when the source of heat is a flow of a turbulent heat-liberating medium, and the heat-receiving object is the wall of the apparatus. According to this method the case of complex heat exchange by using an introduced generalized coefficient of thermal conductivity, taking into account the radiant and convective forms of heat transfer, is reduced to the examination of a problem of convective–conductive heat transfer in a cylindrical channel, and the corresponding differential equation is transformed by using the theory of similarity in a functional connection of dimensionless parameters.

The process of steady-state heat exchange between a turbulent flow of absorbing medium with the source of heat and the wall of the apparatus, without taking into account the energy diffusion (Fig. 1) is described by the equation

$$\mathrm{div}\,(q_{rad}) + \mathrm{div}\,(q_{conv}) = 0\,. \qquad (1)$$

The convective heat transfer depends both on the direction of the regulated movement of the medium and on the turbulent vortices.

We will introduce a generalized vector which unifies the radiant and turbulent heat transfer

$$q^* = \lambda^* \nabla T\,. \qquad (2)$$

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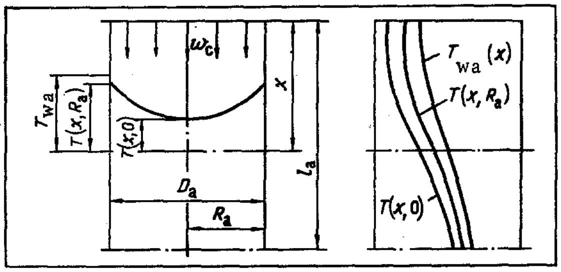

Fig. 1

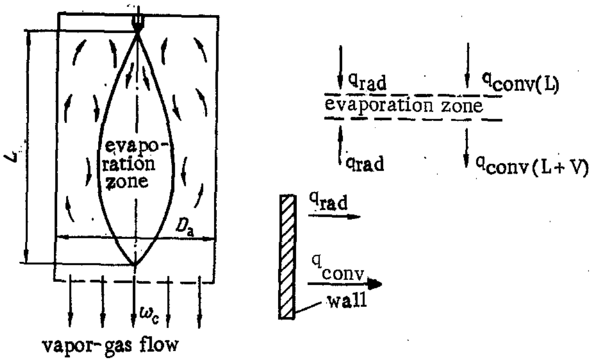

Fig. 2

Fig. 1. The determination of heat transfer for a turbulent flow of absorbing medium and apparatus walls.

Fig. 2. The determination of heat transfer in the area of evaporation of the torch ($L = L_{to}$) of the atomized liquid.

The use of the generalized coefficient of thermal conductivity λ^* enables the known equation of convective-conductive heat transfer of an axisymmetrical moving flow of a medium in a cylindrical channel to be used for describing such a complex case

$$\frac{\partial^2\theta}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial\theta}{\partial r} + \frac{\partial^2\theta}{\partial x^2} - \frac{w_c}{a^*} \cdot \frac{\partial\theta}{\partial x} = 0. \tag{3}$$

The unknown function is represented in the form of a product by means of the Fourier method $\theta(x, r) = \theta(x)\theta(r)$.

Taking into account that the solution of the problem has already been examined in detail [3], we will dwell only on those distinguishing features which are introduced by the new conditions.

The following boundary conditions were adopted for the solution:

$$\text{where } r = R_a \qquad -\lambda_{rad}\theta'(r)|_{r=R_a} = \alpha_{rad}\theta(r)|_{r=R_a},$$
$$\text{where } x = l_a \qquad -\lambda_{rad}\theta'(x)|_{x=l_a} = \alpha_{rad}\theta(x)|_{x=l_a}.$$

The boundary conditions when the absorbing medium enters the zone of the apparatus is described by the following equation:

$$\theta(r)_{x=0} = \theta_1 = (\overline{T}_{wa} - \overline{T}_1).$$

The solution leads to a criterion connection of general form

$$\frac{\overline{\theta}(x, r)}{\theta_1} = f\left(\frac{w_c D_a}{a^*}, \overline{k}D_a, A_{wa}\frac{\overline{T}_{wa}}{\overline{T}_1}, \frac{l_a}{D_a}\right). \tag{4}$$

The criterion of convective-radiant heat exchange in the turbulent flow of the absorbing medium can be represented in the form

$$\frac{w_c D_a}{a^*} = \frac{w_c D_a}{\nu} \cdot \frac{\nu}{a} \cdot \frac{1}{\frac{a_{rad}}{a} + \frac{a_{turb}}{a}}.$$

The magnitude $\overline{\theta}(x, r) = (\overline{T}_2 - \overline{T}_1)$ represents the difference of the average temperatures of the flow at the outlet and inlet, and the relationship $(\overline{\theta}(x, r))/\theta_1 = (\overline{T}_2 - \overline{T}_1)/(T_{wa} - T_1)$ is theheat exchange criterion for this zone.

Hence the final temperature of the medium is determined by the functional connection of the criteria

$$\frac{\overline{T}_2 - \overline{T}_1}{\overline{T}_{wa} - \overline{T}_1} = f'\left(\frac{wD_a}{\nu}, \overline{k}D_a, A_{wa}\frac{\sigma_0\overline{T}_1^3}{\overline{k}\lambda}, \frac{\nu}{a}, \frac{\overline{T}_{wa}}{\overline{T}_1}, \frac{l_a}{D_a}\right). \tag{5}$$

The criterion connection is obtained from the transcendental equation. In this case the principle of formation of dimensionless criteria is subordinated to the Federman theorem [4].

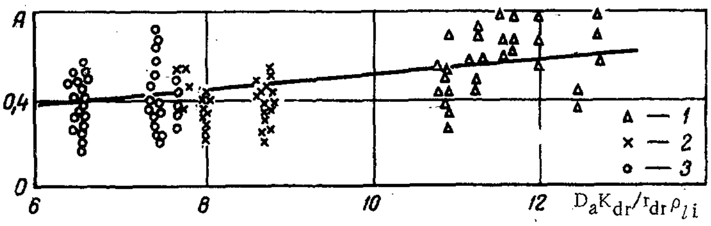

Fig. 3. Relationship between the lengths of the nonevaporating part of the torch and the criterion of the absorbing capacity of the drop. $A = 7.08\, L_{to}/D_a/[\exp(-0.53\bar{T}_{wa}/T_1^{\prime})]\, Fr^{0.29}$ [1) $T_{der}/T_1^{\prime} = 1.9$; 2) 1.65; 3) 1.5].

The Buger criterion, which characterizes the absorbing capacity of the medium, $Bu = \bar{k}D_a$ is determined at constant diameter of the apparatus, by the value of the coefficient of the attenuation of the beam k. The absorbing capacity of the homogeneous medium a_c which in a general case consists of radiation absorbing gases which contain particles is determined by the equation

$$a_c = 1 - \exp(k_0 + k_g)\, l_g. \tag{6}$$

The absorbing capacity of the clouds of particles can be taken into account by the dimensionless parameter $K_1 = (D_aK_{sol}/r_{sol}\rho_{sol})$ which represents a variable part of the index of degree of expression for calculation of the coefficient of illumination φ' of the particles along the axis of the cylindrical reactor which contains the gas suspension [5].

$$\varphi' = \exp\left[-0.6D_a \frac{3K_{dr}}{4r_{sol}\,\rho_{sol}}\right]. \tag{7}$$

The absorbing capacity of the gas in a more widespread case of drying aqueous solutions in an air medium for a single diameter of the apparatus is determined by the partial pressure of the water vapors

$$K_2 = \frac{m_{li}}{m_{li} + m_{air} \cdot 0.622}.$$

The results of the preliminary investigations of the aerodynamic torch of atomized liquid carried out by us and the appraising calculations show that for the level of turbulence recorded in the apparatus [5, 6], the Reynolds criterion, which is dependent on the average speed of the medium along the cross section of the apparatus in the range of studied volume discharges, is not the determining parameter (for the majority of systems its value does not exceed 300 and corresponds to the laminar flow system). In view of this the velocity of the gas–liquid stream flowing out from the jet (the Froude number for the gas–liquid stream $Fr = (w_{mix}^2/gd_0)$) is examined as the main hydrodynamic factor which influences the heat exchange. As follows from the theory of the turbulent gas torch [7], the Froude criterion quite clearly characterizes the turbulence and the hydrodynamic long range of the torch. Obviously, not only the length of the heat exchange section l_a/D_a but also the distance from the beginning of this section to the source of turbulent disturbances, i.e., the nozzle of the jet, can be a substantial determining factor, L_a/D_a.

Representing the dimensional parameters w_cD_a/ν, $\bar{k}D_a$, $\sigma_0\bar{T}_1^3/\bar{k}\lambda$, ν/a in the form of the Boltzman criterion ($Bo = w_cc_c\rho_c/\sigma_0\bar{T}_1^3$) and omitting the criterion of the absorbing capacity of the wall A_{wa}, which remains constant for the conditions of the experiments in one apparatus, we will obtain the functional connection of the criteria in the form

$$\frac{\bar{T}_2 - \bar{T}_1}{\bar{T}_{wa} - \bar{T}_1} = f''\left(\frac{\bar{T}_{wa}}{\bar{T}_1},\ Fr,\ K_1,\ K_2,\ \frac{l_a}{D_a},\ \frac{L_a}{D_a},\ Bo\right). \tag{8}$$

In the case of evaporation in an apparatus a pure liquid which does not contain salts, the criterion K_1 for the zone of superheating of the flow of the vapor–gas medium following the evaporation zone will not have any meaning.

When a torch of atomized liquid is introduced into the apparatus evaporation of the drops and superheating of the vapor–gas flow occurs by means of the heat supply from the walls (Fig. 2). In these conditions, Eq. (1) includes the vector of the directed regulated enthalpy transfer $\rho_cc_cT'_1$ and the energy necessary for evaporation of the liquid K_k on the line q_{evap} in the form of an evaporation component K_{dr}

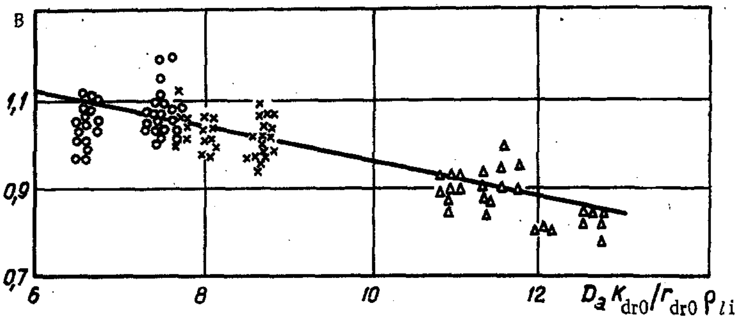

Fig.4. Relationship between the average temperature of the vapor–gas medium at the end of the evaporation zone and the criterion of the absorbing capacity of the cloud of drops. The designations are the same as in Fig.3. $B = 0.127\,(T_{der} - T_1')/(T_{wa} - T_1')/(T_{wa}/T_1')^{-0.81}Fr^{-0.625}$.

$$q'_{conv} = w_c(\rho_c c_c T_1' - K_{dr} q_{evap}) \tag{9}$$

and the vector of transfer of enthalpy and energy of evaporation of the liquid by means of turbulent vortices

$$q''_{conv} = -(\lambda_{turb}\nabla T - D_{turb} q_{evap}\nabla K_{dr}). \tag{10}$$

We will use the determination of the derived temperature

$$T_{der} = \bar{T}_2' + \frac{q_{evap}\, m_{li}}{c_{vg}(m_{li} + m_{air}) + c_{sol}\, a'_{sol}\, m_{li}}, \tag{11}$$

which the medium would acquire at the end of the zone of evaporation on condition that the heat lost on evaporation of the liquid contained in the medium is discharged for its superheating from the actual final temperature $\bar{T}_2'$.

Introducing the derived temperature, the equation of energy transfer (1) can be written in the form

$$\operatorname{div}(w_c \rho_c c_c T_{der}) + \operatorname{div}(-\lambda^*_{rad}\nabla T_{der}) + \operatorname{div}(-\lambda^*_{turb}\nabla T_{der}) = 0. \tag{12}$$

In view of the extreme complexity of the processes taking place in the torch, we will confine ourselves to examination of an approximate system. In the case of full instantaneous evaporation of the atomized liquid, which is evenly distributed in the carrier gaseous medium entering into the zone with a single speed over the whole lateral cross section, the process will be written by the same criterion connection as in the process of heat exchange of turbulent flow of the absorbing medium with the walls of the apparatus. In this case the final temperature of the flow in the zone corresponds with the derived temperature T_{der}. Evidently the process of heat transfer in the evaporating zones with similar geometrical conditions of input and evaporation of the gas–liquid stream can be represented in the form of two functional connections in which the criterion of heat transfer $(T_{der} - T_1')/(T_{wa} - T_1')$ is the nondetermining parameter and the dimensionless length of the nonevaporating torch is L_{to}/D_a:

$$\frac{T_{der} - T_1'}{T_{wa} - T_1'} = f'''\left(\frac{T_{wa}}{T_1'},\ Fr,\ Bo',\ K_1,\ K_2,\ \frac{T_{der}}{T_1'}\right); \tag{13}$$

$$\frac{L_{to}}{D_a} = f^{IV}\left(\frac{T_{wa}}{T_1'},\ Fr,\ Bo',\ K_1,\ K_2,\ \frac{T_{der}}{T_1'}\right). \tag{14}$$

The criterion of the absorbing capacity of the clouds of drops K_1 in the given case is examined for boundary conditions at the inlet of the zone (in the case of initial values of the dispersion r_{dr_0} and of the mass concentration of liquid K_{dr_0} in the volume of atomizing air V_{g0}). The applicability of the functional connections obtained is limited by the conditions of the geometrical similarity, which are characterized by the factor of concentration d_0/D_a and the angle of opening of the torch α_{to}.

In the limits recommended in the technology of pneumatic atomization the relationships of the discharges of atomizing air in the liquid and the technically useful diameters of the apparatus, the Buger criterion, which takes into account the absorbing capacity of the vapor–gas phase, varies negligibly, and therefore this influence in the form of the parameter K_2 can be neglected.

The Boltzman criterion for the evaporation zone is determined according to the formula $Bo = \bar{w}_c \bar{c}_c \bar{\rho}_c / \sigma_0 (T_1')^3$. Since in this zone the medium is not homogeneous, it is hence a question only of specific derived values of the velocity $\bar{w}_c$, the specific heat $\bar{c}_c$ and the density $\bar{\rho}_c$ of the flow of the medium.

The derived specific heat can be determined according to the formula:

$$\bar{c}_c = \frac{c_{li} m_{li} (T_{evap} - T_1') + q_{evap} m_{li} + \bar{c}_{vg} m_{li} (\bar{T}_2 - T_{evap}) + c_{air} m_{air} (T_2 - T_1')}{(m_{li} + m_{air})(T_{der} - T_1')}. \tag{15}$$

The derived density of the medium is given by

$$\bar{\rho}_c = \frac{4(m_{li} + m_{air})}{\pi D_a^2 \bar{w}_c 3600}. \tag{16}$$

Analysis of the data obtained did not reveal a relationship between the nondetermining parameters (13), (14) and the criterion Bo', although the latter varied almost by 3 times at the expense of the speed and the specific heat of the medium.

In view of the fact that for the systems studied the volume discharge of the medium is dependent on the laminar nature of the flow, the virtual absence of the influence of the criterion Bo' on the intensity of the heat and mass transfer is quite according to the rules.

The simplex T_{der}/T_1' varied insignificantly; its influence was very small.

As as result of treatment of the experimental data the criterion relationship was obtained.

The dimensionless length of the nonevaporating part of the torch of atomized liquid (the length of the evaporation zone) is determined by the expression

$$L_{to}/D_a = [\exp(-0{,}53\bar{T}_{wa}/T_1')]\,\mathrm{Fr}^{0{,}29}\left(0.170 + 0.015\frac{D_a K_{dr}}{r_{dr}\rho_{li}}\right). \tag{17}$$

The dimensionless temperature at the end of the evaporation zone

$$\frac{T_{der} - T_1'}{\bar{T}_{wa} - T_1'} = (\bar{T}_{wa}/T_1')^{-0{,}81}\mathrm{Fr}^{-0{,}265}\left(174.4 - 5.3\frac{D_a K_{dr}}{r_{dr}\rho_{li}}\right). \tag{18}$$

The investigated regions of variation of the criteria correspond to the main systems of drying in the tube with heat supply from the walls.

The mean square error, calculated with a probability of 95%, for Eq. (17) was ±11%, for Eq. (18) it was ±10%. The analysis of the relationships obtained showed that the main factors on which the length of the torch depends are the temperature of the wall, the Froude criterion, and the criterion of the absorbing capacity of the cloud of drops.

Increase of the wall temperature sharply reduces the length of the nonevaporating torch, obviously, most of all owing to the increase of the radiant flow of heat and the intensive evaporation of the cloud of drops.

In the case of increase of the Fr, the torch becomes longer as a result of the longer range of the stream, although at the same time, as a result of the increasing turbulence, the heat transfer from the wall to the torch is intensified and as a result of the length of the evaporation zone is reduced with increase of Fr. Hence the temperature of the medium at the end of evaporation decreases. Obviously this takes place as a result of intensification (at a much higher level of turbulence in the apparatus) of the interphase heat transfer of the system gas–drops and of the completion of the process of evaporation of the drops in the case of a smaller temperature difference between the gas and the drops.

The criterion of the absorbing capacity $D_a K_{dr_0}/r_{dr_0}\rho_{li}$ in the range of values studied has considerable influence on the length of the torch (Fig. 3). With a constant diameter of the apparatus D_a and density of the liquid ρ_{li} the criterion $D_a K_{dr_0}/r_{dr_0}\rho_{li}$ increases with increase of the initial specific discharge of liquid or with decrease of the initial dimension of the drops. Hence the absorbing capacity of the torch and the total radient thermal flow to it increases. However, at the same time the coefficient of irradiation of the drops, moving along the axis of the apparatus, decreases, which must lead to a lengthening of the evaporation zone. Evidently the influence of the second factor predominates.

Increase of the criterion $D_a K_{dr_0}/r_{dr_0}\rho_{li}$ leads to a decrease of the temperature in the end of the zone (Fig. 4). This fact is obviously explained by the fact that as a result of the increasing absorbing capacity of the cloud of drops, the flow of the radiant heat directly to the drops is strengthened. The process of evaporation is therefore completed at lower temperatures of the vapor–gas medium.

The following ranges of measurement of the criteria were investigated:

$$\frac{D_a K_{dr}}{r_{dr}\rho_{li}} = (6.5-12.5); \quad \frac{m_{li}}{m_{li} + m_{air}\,0.622} = (0.62-0.76);$$

$$\frac{T_{der} - T_1'}{\bar{T}_{wa} - T_1'} = (1.50-2.46); \quad \frac{L_{to}}{D_a} = (0.93-4.65); \quad \frac{\bar{T}_{wa}}{T_1'} = (2.4-3.7);$$

$$Fr = (0.16\cdot 10^6 - 0.72\cdot 10^6); \quad \frac{T_{der}}{T_1'} = (1.47-1.95); \quad Bo' = (0.19\cdot 10^{-9} - 0.49\cdot 10^{-9}).$$

The criterion relationships (17), (18) can evidently be used for calculation of the atomizing driers with a narrow torch pneumatic jet with an angle of the opening of the free torch $\alpha_{to} \simeq 14$-$25°$ and with a geometrical factor of concentration of the torch by the walls of the apparatus $d_0/D_a \simeq 0.01$. Experimental confirmation of the relationships obtained was obtained by studying the process of the atomizing drier of some types of technological pulps in apparatus with a diameter of 130 and 300 mm, where the relationships (17), (18) were used for calculation of the parameters of the optimal system and the dimensions of the evaporation zone.

NOTATION

a	is the thermal diffusivity, m/sec^2;
$a^* - \lambda^*/\rho_c c_c$	is the generalized thermal diffusivity, m^2/sec;
$a_{rad}/a = 16/3 \cdot \sigma_0 T^3/k\lambda$	is the criterion of the radiant conductive heat transfer;
$a_{turb}/a = x_1(wD_a/\nu)\cdot\nu/a$	is the criterion of convective heat transfer;
a'_{sol}	is the salt content in the solution, kg/kg;
c	is the specific heat, J/kg·deg;
c_{vg}	is the specific heat of the vapor–gas medium at the evaporation temperature of the liquid, J/kg·deg;
D_a	is the diameter of the apparatus, m;
D_{turb}	is the coefficient of turbulent exchange of liquid in the gas, m^2/sec;
d_0	is the diameter of the aperture of the liquid nozzle of the jet, m;
$f, \ldots, f^{IV}$	are the signs of the functional connection;
K_{sol}, K_{dr}	are the concentration of particles of drops of liquid in the volume of the atomizing air, kg/m^3;
k_g	is the coefficient of attenuation of the flux of the radiant energy by the gas; 1/m;
k_0	is the coefficient of attenuation of the flow of the radiant energy by a cloud of particles or drops, 1/m;
k	is the mean coefficient of total attenuation of the flux of the radiant energy, 1/m;
L_a	is the distance from the jet to the beginning of the heat transfer section, m;
L_{to}	is the length of the nonevaporating torch (evaporation zone), m;
l_a	is the length of the heat transfer section, m;
l_g	is the length of the beam which is equal to the thickness of the gas layer, m;
m_{li}	is the discharge of liquid, kg/h;
m_{air}	is the discharge of atomizing air, kg/h;
q_{conv}	is the vector of the convective heat transfer, $J/m^2\cdot sec$;
$q'_{conv} = w_c\rho_c c_c T$	is the vector of the convective transfer of the enthalpy of the medium dependent on the direction of the orderly movement, $J/m^2\cdot sec$;
$q''_{conv} = -\lambda_{turb}\nabla T$	is the vector of heat transfer by using turbulent vortices, $J/m^2\cdot sec$;
$q_{rad} = -\lambda_{rad}\nabla T$	is the vector of radiant heat transfer, $J/m^2\cdot sec$;
q'_{evap}	is the latent heat of the evaporation of liquids taking into account the necessary heat for heating up to the temperature of equilibrium evaporation, J/kg;

R_a	is the radius of the apparatus, m;
r	is the current radius of the apparatus, m;
r_{dr_0}	is the initial volume-surface radius of the drop, m;
r_{sol}	is the radius of the particles, m;
$\overline{T}_1$	is the initial average temperature of the medium on the superheating section, °K;
T_1'	is the temperature of the medium at the beginning of the evaporation zone, °K;
$\overline{T}_2$	is the final average temperature of the medium on the superheating section, °K;
$\overline{T}_2'$	is the average temperature of the medium at the end of the evaporation zone, °K;
$\overline{T}_{wa}$	is the average temperature of the wall, °K;
w_c	is the speed of the flow of the medium, m/sec;
$w_c D_a/\nu$	is the Reynolds criterion;
w_{mix}	is the initial velocity of the gas–liquid mixture, m/sec;
x	is the distance along the axis of flow of the medium, m;
x_1	is the transition factor from the velocity of the flow and its lateral dimension to the velocity and the length of the path of the turbulent mass in the flow;
θ	is the difference between the temperature of the wall and the medium, deg;
θ'	is the temperature gradient, deg/m;
λ	is the coefficient of thermal conductivity of the medium, J/m·sec·deg;
$\lambda^* = \lambda_{rad} + \lambda_{turb}$	is the generalized thermal conductivity coefficient, J/m·sec·deg;
$\lambda_{rad} = 16/3 \cdot \sigma_0 T^3/k$	is the specific coefficient of radiant thermal conductivity [3], J/m·sec·deg;
$\lambda_{turb} = D_{turb}\rho_c c_c$	is the specific coefficient of turbulent heat conductivity corresponding to the gradient of the derived temperature ∇T_{der}, J/m·sec·deg;
ν	is the coefficient of kinematic viscosity of the medium, m/sec;
ν/a	is the Prandtl criterion;
ρ	is the density, kg/m³;
ρ_0	is the concentration of particles in the medium, kg/m³;
σ_0	is the coefficient of radiation of an absolutely black body;
$\sigma_0 = 5.7 \cdot 10^{-8}$ J/m²·deg·K⁴·sec;	
∇	is the gradient.

Subscripts

g	is the gas;
li	is the liquid;
dr	is the drop;
conv	is the convective;
m	is the mass;
(m + v)	is the mass of the liquid and the vapor;
sol	is the solid phase, particles;
v	is the vapor, vapor formation;
0	is the initial value of the parameter.

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