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Electric field induced heat transfer enhancement in a gas–solid suspension heat exchanger

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Abstract—The paper deals with the study of heat transfer and hydromechanics of gas-disperse flows under the action of a transverse electric field. An analysis of the specific features of aerosol flow at different relationships between the electric and hydrodynamic forces acting on particles is carried out. The conditions have been identified which provide the use of an electric field at maximum efficiency for the enhancement of heat transfer to gas suspension flows and of the intercomponent heat transfer.

INTRODUCTION

THE EFFECT of electric fields on heat transfer of gas-disperse systems rests on a change in the hydromechanics of flow due to the motion of particles under the action of Coulombic forces. The available publications pertaining to the effect of fields on gas-disperse flows deal with both the problems of generation or elimination of triboelectricity [1–4] and the study of flow electrization by applying a potential difference between the electrodes in a duct [5]. In both cases, an increase in the hydraulic losses for suspension transport is observed as well as the similarity between the transverse distributions of true volumetric concentrations of particles characterized by the presence of a minimum in the central regions of a duct [4, 5].

The study of the effect of electric fields on convective heat transfer and hydraulic resistance of a gas suspension, containing spherical glass particles ($\bar{d}_s = 30$ μm), in a rectangular duct in the ranges of flow-rate mass concentrations $\mu = 0$–2.5 and of the Reynolds numbers $Re_D = 1460$–5840 depending on the polarity and frequency (0–60 Hz) of the 7.9×10^5 V m^{-1} electric field, have shown that the enhancement of the test section length-averaged heat transfer amounts to 60%, while the local heat transfer characteristics were not studied [5]. No study has also been made of the possibility for the enhancement of heat transfer in flows with electrically conducting particles whose inter-electrode motion, as compared with dielectric dispersed material, is distinguished by a higher intensity and stability due to a rather rapid inductive recharging of particles for the time of elastic collision with the electrode [6].

In this work the main attention was paid to the study of local thermal and hydrodynamic characteristics determining the specific features of electric field effect on heat transfer in gas-suspension flows containing an electrically conducting dispersed component.

EXPERIMENTAL APPARATUS AND MEASUREMENT PROCEDURE

The experiments were carried out in a loop closed for a dispersed component and open for air (Fig. 1). By means of a screw feeder ③ rotated at a variable speed the dispersed material was supplied to an air flow delivered from compressors through a receiver and a system of pressure regulators ㉒ into the lower part of the test section ②. Having passed the removable test section, ② and ④, the gas suspension entered a cyclone ⑤ (Fig. 1). The dispersed material gave up heat in a refrigerator ⑥, entered a feeder bunker ⑧, while the air, which had passed through an orifice plate ⑨, was vented to the atmosphere.

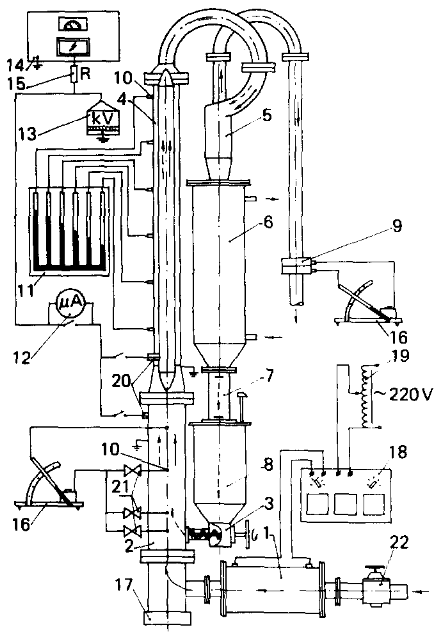

FIG. 1. Schematic of the experimental apparatus: ① electric heater; ② lower portion of the test section for the investigation of intercomponent heat transfer in an electric field; ③ screw feeder; ④ upper portion of the test section for the investigation of the hydromechanics in an electric field; ⑤ cyclone; ⑥ refrigerator; ⑦ particle circulation meter; ⑧ feeder bunker; ⑨ orifice plate; ⑩ static pressure tapping; ⑪ battery manometer; ⑫ microammeter; ⑬ electrostatic kilovoltmeter; ⑭ high-voltage source; ⑮ ballast electrical resistance; ⑯ micromanometers; ⑰ site of movable thermocouple insertion; ⑱ Wattmeter; ⑲ voltage regulator; ⑳ high-voltage bushing; ㉑ pressure divider; ㉒ pressure regulators.

NOMENCLATURE

- b width of plane channel
- c specific heat
- c_f drag coefficient for flow around a particle
- D hydraulic diameter of duct
- $\bar{d}_s$ mean particle diameter
- E electric field strength
- F_c viscous resistance force acting on particle
- G mass flow rate of component
- g acceleration due to gravity
- h interelectrode gap
- k, v^a parameters of the linear approximation of viscous resistance force acting on particle
- L duct length
- m mass of particle
- Nu Nusselt number, $Nu_D = \frac{\alpha D}{\lambda}$, $Nu_s = \frac{\alpha_s d_s}{\lambda}$
- $\langle Nu \rangle$ Nusselt number averaged over test section length
- p pressure
- q particle charge
- q_w specific heat flux on duct wall
- Q_x volumetric particle flux to duct wall
- Re Reynolds number, $Re_D = \frac{iD}{\nu}$, $Re_s = \frac{(v_f - v_s)d_s}{\nu}$
- t temperature
- U voltage across electrodes
- v velocity
- v_b particle suspension velocity
- w_p particle volume
- x longitudinal coordinate
- y transverse coordinate.

Greek symbols
- α heat transfer coefficient
- β true volumetric particle concentration
- β_p volumetric flow-rate particle concentration, $\frac{G_s \rho}{G \rho_s}$
- $\gamma(q)$ differential distribution of particle tribocharges
- ε relative dielectric permittivity of gas
- ε_0 dielectric permittivity of free space
- λ thermal conductivity
- μ flow-rate mass concentration, $\frac{G_s}{G}$
- ν kinematic viscosity of gas
- Π duct perimeter
- ρ density
- σ_τ viscous stress at duct wall
- τ time
- Φ_w reduced density of the flux of charged particles to duct wall
- Ω area of duct cross-section

Subscripts
- D quantity based on hydraulic diameter of duct
- E electric field
- f quantity characterizing pure gas motion
- s dispersed component
- x projection of vector on x axis
- y projection of vector on y axis
- 1 preliminary charged particles
- 2 recharged particles.

Superscripts
- $\bar{}$ quantity averaged over the duct cross-section
- $'$ value at duct entrance
- $*$ dimensionless quantity.

The test section for the investigation of the hydromechanics and intercomponent heat transfer of a gas suspension consisted of two parts: the lower one ② (Fig. 1) in the form of a rectangular 5 × 50 mm duct 0.3 m long and the upper one ④ in the form of a coaxial channel ($D_1/D_2 = 25/37.5$ mm) 2 m long. In hydromechanical experiments the flow rates of air, G, and of the dispersed material, G_s, the static pressure drop Δp, steady electric field strength U, and convective electric current were measured. Owing to the difficulty of direct measurements of the local hydromechanical characteristics of gas suspensions in narrow interelectrode gaps, these characteristics were obtained by simultaneously solving the equations of motion for a carrier medium and pure gas

$$(p + dp)\Omega = p\Omega + \frac{F_c}{w_p} d\beta + \sigma_\tau \Pi \, dx + \rho g \Omega \, dx$$

$$(p_f + dp_f)\Omega = p_f \Omega + \sigma_{\tau,f} \Pi \, dx + \rho g \Omega \, dx. \quad (1)$$

Assuming, in the first approximation, the validity of the additive superposition principle for hydraulic losses [7], i.e. $\sigma_\tau = \sigma_{\tau,f}$, the relations were obtained for the calculation of the true volumetric concentration in a duct from the experimentally measured distributions of pressure losses. Taking into account the linear approximation for the viscous resistance force [8], the following relation was obtained for the Stokes and transition flow regimes around particles

$$\bar{\beta} = \frac{\bar{v}\mu}{v - v^a} \frac{\rho}{\rho_s} + \frac{d_s^2}{18\rho\nu k_c(\bar{v} - v^a)} \frac{d(p - p_f)}{dx} \quad (2)$$

where v^a and k_c are calculated with regard for the maximum and minimum relative velocities of dispersed material by the relations from ref. [8]. For the self-similar law of flow around particles ($Re_s \geqslant 10^3$, $c_f = 0.43$)

$$\bar{\beta} = \mu \frac{\rho}{\rho_s} + \frac{2}{3} \frac{d_s}{\bar{v}^2 c_f \rho} \frac{d(p-p_f)}{dx} + \sqrt{\left\{ \left[\mu \frac{\rho}{\rho_s} + \frac{2}{3} \frac{d_s}{\bar{v}^2 c_f \rho} \frac{d(p-p_f)}{dx} \right]^2 - \mu^2 \left(\frac{\rho}{\rho_s} \right)^2 \right\}}. \quad (3)$$

The validity of the relations obtained was confirmed by the measurements of length-averaged volumetric concentrations of particles with the use of the cut-off method realized in the lower part of the test section (Fig. 1). The uncertainty of calculation of the cross section-averaged volumetric concentrations of particles according to relations (2), (3) was within $\pm 5\%$. The hydromechanical measurements were conducted in the upper part of the test section ④ (Fig. 1) with spherical bronze particles of $\bar{d}_s = 141\ \mu m$ within the ranges of Re_D numbers $Re_D = 4 \times 10^3 - 1.8 \times 10^4$, flow-rate mass concentrations $\mu = 0$–13 and electric field strengths $\bar{E} = 0$–10^6 V m^{-1}.

For the investigation of the intercomponent heat transfer, the measurements were carried out in the lower part of the test section ② (Fig. 1). Air, before it was mixed up with the particles, had been heated in a tubular electric furnace ①. In the course of the experiments the measurements of the following parameters were made: the temperature of particles that entered the duct, the temperature of air over the height of the test section, high voltage, flow rates of the components, pressure losses in the test section, water flow rate in the refrigerator ⑥ and power input to the electric heater ①. The distribution of temperatures of the gas component over the test section height was measured by a moving sheathed thermocouple introduced into the flow through a plug ⑪ (Fig. 1). The dispersed material consisted of bronze particles with $\bar{d}_s = 255\ \mu m$. The experiments were carried out within the ranges of $Re_D = 10^4$–2.5×10^4, mass flow rates $\mu = 0$–2.5 and field strengths $\bar{E} = 0$–10^6 V m^{-1}. With regard for negligible heat losses through the walls of the lower part of the test section, the dispersed material temperature and the quantity of heat transferred to it were calculated from the heat balance equation. The surface of the dispersed material and its relative velocity were determined from the true volumetric concentration $\bar{\beta}$ calculated by relation (2). The intercomponent heat transfer coefficients were calculated by the quantity of heat transferred to the dispersed material, by its surface area and mean logarithmic temperature difference between the components.

For the investigation of heat transfer to a gas suspension flow, the version of the test section in the form of a coaxial duct ($D_1/D_2 = 25/37$ mm) was used (Fig. 2). The walls of the lower portion—the section of hydrodynamic stabilization 0.6 m long—were earthed through a microammeter ⑬ (Fig. 2). This section served also to tribocharge the particles during their pneumatic transport. The upper portion $L = 1.5$ m long consisted of an inner heat releasing ③ and outer high-voltage ① electrodes. The earthed tube ③ contained an electric heater ④, which provided the boundary condition q_w = const., and thermocouples ⑤ which were embedded along the heat transfer surface length. In the experiments, the flow rates of the components, pressure losses over the test section, inlet gas suspension temperature, heater power, readings of thermocouples, and high voltage were measured, the water flow rate in the refrigerator ⑥ (Fig. 1) was controlled as well as the current over the tribocharging section. The dispersed material consisted of corundum particles with $\bar{d}_s = 78\ \mu m$ and steel particles with $\bar{d}_s = 75$ and $141\ \mu m$. The experiments were run within the ranges: $Re_D = 3 \times 10^3$–1.3×10^4, $\mu = 0$–8 and $\bar{E} = 0$–10^6 V m^{-1}. The local heat transfer coefficients were calculated, neglecting the temperature slip of the components, from the values of q_w and from the difference between the wall temperature and enthalpy-averaged gas suspension flow temperature at the section considered.

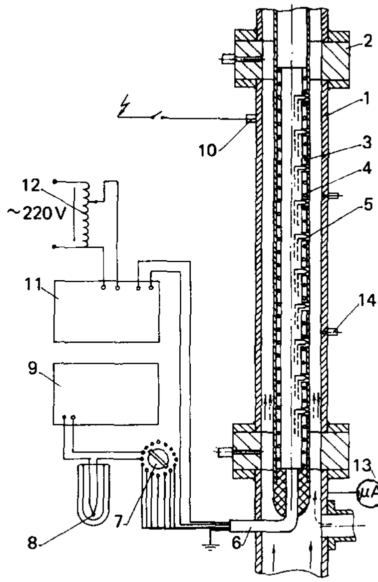

FIG. 2. Test section for the study of heat transfer to a gas suspension in an electric field: ① high-voltage electrode; ② insulating flange; ③ inner heat releasing electrode; ④ electric heating coil; ⑤ thermocouples; ⑥ leads of thermocouples, electric heater and of earth; ⑦ switcher of thermocouples; ⑧ cold junction of thermocouples; ⑨ potentiometer; ⑩ high-voltage bushing; ⑪ Wattmeter; ⑫ voltage regulator; ⑬ microammeter; ⑭ static pressure tapping.

EXPERIMENTAL RESULTS

In investigating the heat transfer to a gas suspension flow with corundum particles it has been found that over the tribocharging section these particles acquire the positive charge as a result of which, in the case of the like polarity of the high-voltage electrode, the dispersed material moves radially toward the heat transfer surface (Fig. 2). The change of polarity leads to a decrease in heat transfer as compared with the case of no external field. An alternating 50-Hz field does not exert any appreciable effect on heat transfer to a gas suspension with dielectric particles.

The specific features of the steady electric field effect on the local heat transfer of a gas suspension containing corundum particles (Fig. 3) correspond qualitatively to the longitudinal distributions of the flow density of glass particles toward a duct wall, Φ_w, found in ref. [5]. Thus, the maximum heat transfer in the region $x/D = 20$–25 (Fig. 3) is explained by the influx of charged particles to the heat transfer surface, after which the tendency is observed toward heat transfer stabilization as a result of the recharging of dispersed material and its motion in the direction of the high-voltage electrode. The value $\bar{E} = 7 \times 10^5$ V m^{-1} is an optimum one, since at higher values only the redistribution of the heat transfer coefficients occurs with the mean value remaining the same (Fig. 3). When the flow-rate mass concentration of dispersed material increases up to $\mu \simeq 6$ at fixed field strengths, an increase in the relative heat transfer coefficient is observed which at $\mu > 6$ is replaced by the self-similarity α_E/α_0 with respect to the flow-rate concentration of particles. The maximum heat transfer enhancement occurred in the case of the minimum velocity of pneumatic transport ($Re_D = 4.6 \times 10^3$). At the flow velocity of $Re_D = 1.5 \times 10^4$, the electric field effect on heat transfer did not exceed 10%. A comparison between the increase of the relative gas suspension flow heat transfer and the relative increase of the aerodynamic resistance in the electric field shows a higher rate of increase of heat transfer. For example, a 43% increase of α_E is associated with a 10% increase in Δp.

Taking into account the fact that the use of a gas suspension with electrically conducting particles as a heat transfer agent is more efficient as compared with dielectric particles, gas-disperse systems with a conducting solid component were used in further investigations. Just as in the experiments with dielectric particles, the influence of the field on heat transfer to a gas suspension flow with electrically conducting dispersed material is most effective at minimum, for the pneumatic transport, Reynolds numbers ($Re_D = 3 \times 10^3$). The degeneration of field effect on heat transfer to a gas suspension occurs at $Re_D > 1.5 \times 10^4$. The longitudinal distributions of local heat transfer coefficients in a steady electric field are shown in Fig. 4. The effect of the alternating 50-Hz field on heat transfer to a gas suspension with steel particles of $\bar{d}_s = 141$ μm is insignificant, while with particles of $\bar{d}_s = 78$ μm it is similar to that found for the case of a steady field (Fig. 4), although less effective. Taking into account the fact that at $\bar{E} = 7 \times 10^5$ V m^{-1} there are as yet no random electric breakdowns, the empirical relations for the calculation of the length-averaged relative heat transfer and hydraulic resistance of a gas-suspension of steel particles with $\bar{d}_s = 75$ μm in an alternating electric field have been obtained for this field strength and the numbers $Re_D = (3$–$6.5) \times 10^3$, $\mu = 0.5$–8

$$\frac{\langle Nu_{DE} \rangle}{\langle Nu_{Df} \rangle} = 390 \times Re_D^{-0.68} \mu^{0.36} \quad (4)$$

$$\frac{\Delta p_E}{\Delta p_f} = 2450\, Re_D^{-0.85} \mu^{0.55} \quad (5)$$

which correlate the data for the alternating 50-Hz field to within $\pm 10\%$.

In a steady electric field with $\bar{E} = (3.3$–$6.7) \times 10^5$ V m^{-1} within the ranges $Re_D = (3$–$6.5) \times 10^3$, $\mu = 0.5$–8 for two fractions of steel particles with $\bar{d}_s = 75$ and 141 μm, the empirical relations have been obtained for the calculation of the mean heat transfer

$$\frac{\langle Nu_{DE} \rangle}{\langle Nu_{Df} \rangle} = 3.77 \times 10^7 Re_D^n \mu^{0.2} \left(\frac{\bar{E}}{E_t}\right)^4 \left(\frac{D}{\bar{d}_s}\right)^{-1.75} \quad (6)$$

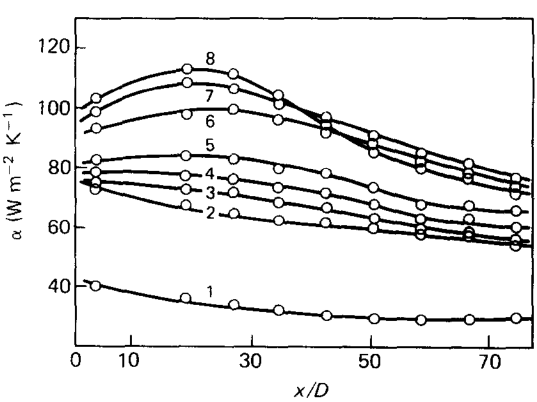

FIG. 3. Local heat transfer to gas-suspension flow containing corundum particles vs steady electric field strength ($Re_D = 4600$). (1) $\mu = 0$, $\bar{E} = 0$; (2–8) $\mu = 6$, $\bar{E} = (0, 0.5, 0.8, 1.5, 4, 7, 10) \times 10^5$ V m^{-1}.

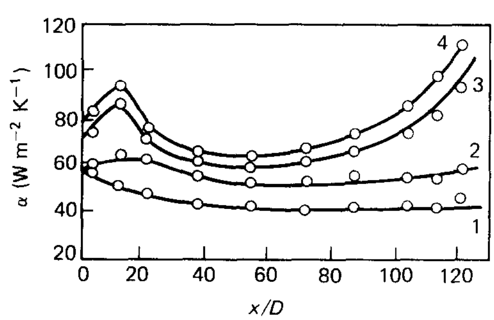

FIG. 4. Distribution of the coefficient of heat transfer to a gas suspension flow ($Re_D = 3 \times 10^3$, $\mu = 4$) containing steel particles with $\bar{d}_s = 75$ μm depending on the steady electric field strength; (1–4) $\bar{E} = (0, 1, 4, 5) \times 10^5$ V m^{-1}.

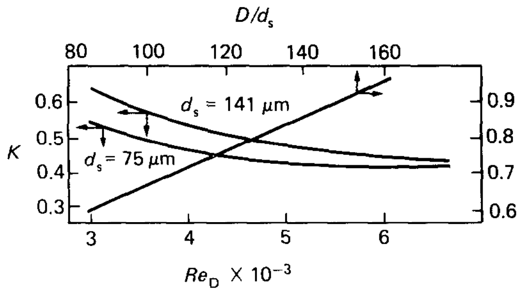

FIG. 5. Dependence of the exponents l and k in equation (7) on the relative dimension $D/\bar{d}_s$ and Re_D number.

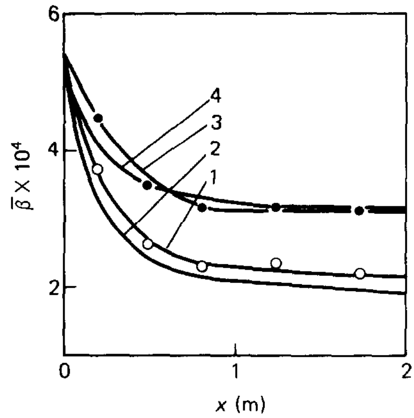

FIG. 7. Experimental and calculated [10] longitudinal distributions of the cross-section-averaged concentrations of particles ($\mu = 1$; $Re_D = 1.15 \times 10^4$). (1 and 2) $\bar{E} = 0$; (3 and 4) $\bar{E} = 10^6$ V m^{-1}.

with an error of $\pm 15\%$ and of the aerodynamic resistance

$$\frac{\Delta p_E}{\Delta p_f} = 3.15 \times 10^{-5} Re_D^l \mu^k \left(\frac{D}{\bar{d}_s}\right)^{3.84} \frac{\bar{E}}{E_t} \quad (7)$$

with an error of $\pm 20\%$. The value

$$E_t = \sqrt{\frac{\rho_s g \bar{d}_s}{\pi^2 \varepsilon \varepsilon_0}} = 1.07 \times 10^5 \sqrt{\rho_s \bar{d}_s g} \quad (8)$$

is the scale of the electric field strength and is determined from the equality of the gravity and Coulombic forces [9]. The exponent n in equation (6) is a linear function of strength and is equal to -1 and -0.7 at $\bar{E} = 6.7 \times 10^5$ and 3.3×10^5 V m^{-1}, respectively. The exponents l and k in equation (7) are the functions of the particle size and Re_D numbers and are determined from the plots presented in Fig. 5.

The measurements of the longitudinal distributions of the duct cross-section-averaged hydromechanical characteristics of gas-suspended bronze particles ($\bar{d}_s = 141$ μm) indicate that the values of their true volumetric concentrations exceed the corresponding values in electrically neutral flows. The specific features of the field effect on the longitudinal distributions of $\bar{\beta}$ at $Re_D = 6.7 \times 10^3$ are shown in Fig. 6(a). At $Re_D > 8 \times 10^3$, the local maximum in the longitudinal set of profiles representing the volumetric concentrations of particles 'disappears' and a minimum 'remains' in the central sections of the duct [Fig. 6(b)]. At $Re_D > 10^4$, the configuration of the longitudinal distributions of concentrations corresponds to the profiles of $\bar{\beta}$ in an electrically neutral gas suspension (Fig. 7). At $Re_D > 1.8 \times 10^4$, the electric field effect on the flow hydromechanics becomes insignificant.

In the experiments on the intercomponent heat transfer in an ascending gas suspension flow, the maximum effectiveness of the field influence on the heating of a dispersed component amounts up to 150%. The results of data processing in the form of the relationships between the intercomponent heat transfer rate (Nu_s) in an electrically neutral flow and the relative velocity of particles (Re_s) agree with the correlations for a nonrestricted gas suspension [7]. The data on the intercomponent heat transfer in an electric field for the following ranges of parameters: $120 < Re_s < 300$; $3.5 \times 10^{-4} < \bar{\beta} < 3 \times 10^{-3}$; $0 \leqslant \bar{E} \leqslant 10^6$

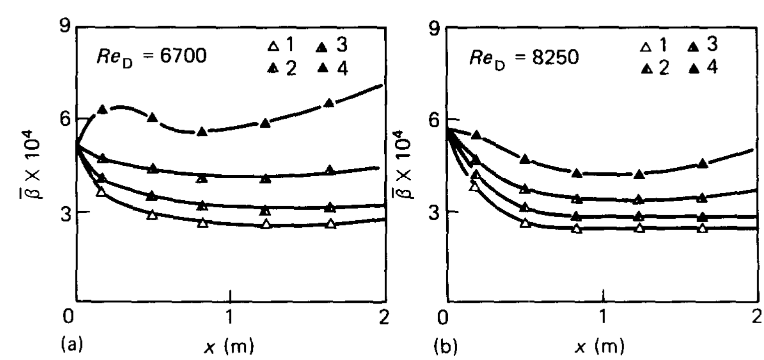

FIG. 6. Electric field effect on the longitudinal distribution of the cross-section-averaged volumetric concentrations of particles in the conditions of ascending pneumatic transport. (1)–(4) $\mu = 1$; $\bar{E} = (0, 4, 7.3, 10) \times 10^5$ V m^{-1}; (a) $Re_D = 6.7 \times 10^3$; (b) $Re_D = 8.25 \times 10^3$.

V m^{-1}, have been correlated to within $\pm 11.5\%$ by the equation

$$Nu_s = 4.27 \times 10^{-3} Re_s^{0.79} \bar{\beta}^{-0.48} \quad (9)$$

An increase in the amount of heat transferred to a dispersed material in an electric field and a decrease of the log–mean temperature difference are 'compensated' by the extension of the heat transfer surface due to a growth of the true volumetric concentration of particles. Moreover, because of the rise of the relative velocity of components in the field, the calculated value of Nu_s corresponds to the greater values of Re_s. As a result, the existence of a strong field around gas-suspended particles does not vary the rate of intercomponent heat transfer and this is indicated by the absence of $\bar{E}$ in equation (9).

ANALYSIS OF RESULTS

In the region of the predominant effect of hydrodynamic forces on particles in gas-suspension flow as compared with electric forces ($Re_D > 10^4$), the dispersed component is accelerated by a gas flow between successive collisions with the duct electrodes. The dynamic equilibrium develops over the stabilized section: the velocity acquired by a particle between two successive collisions with the wall decays after the particle impact on the electrode. Proceeding from these physical concepts, a procedure has been developed for the calculation of the longitudinal distributions of cross-section-averaged hydromechanical characteristics of a gas suspension in an electric field [10] based on the solution of the dispersed component motion equation. The resulting longitudinal sets of profiles for the volumetric concentration of particles correspond to the data obtained in the range $Re_D = 10^4$–1.8×10^4 (Fig. 7).

With a decrease in the gas-disperse flow velocity down to $Re_D = 8 \times 10^3$, the electric forces become commensurable with the aerodynamic ones and this leads to an increase of the relative quantity of charged particles, their involvement into the interelectrode motion and to an increase in the volumetric concentration of dispersed component in the upper portion of the duct [Fig. 6(b)]. This was verified by calculating the motion of spherical bronze particles with $d_s = 150\,\mu$m and $\rho_s = 8.84 \times 10^3$ kg m^{-3} under the conditions of ascending pneumatic transport in a plane vertical channel $h = 10^{-2}$ m wide in the presence of a 7×10^5 V m^{-1} electric field and in its absence. The gas flow was considered in the piston flow approximation, $Re_D = 6 \times 10^3$, the coefficients of the reduction of normal and tangential velocities were equal to $k_n = 0.4$ and $k_\tau = 0.7$. It was assumed that the particles enter the section of field effect as uncharged at the absolute velocities $v_{s,x}|_{x=0} = 0$ and 0.7 m s^{-1} and in different directions with respect to the duct axis. In order to shorten the amount of computation, the introduction of a dispersed component was assumed to be concentrated in four places, while the transverse velocities of particles were assumed to be equal to $v_{s,y} = 0$ and ± 0.05 m s^{-1} before their first collision with the wall as a result of which the dispersed component acquires a specific charge which can be calculated by the method suggested in ref. [9]. In order to obtain the averaged characteristics of the motion of particles and compare the results of computer experiment with the test data, the spatial–temporal averaging [11] was carried out. The longitudinal distributions of the cross-section-averaged volumetric concentrations of particles both in the presence of electric field and in its absence (Fig. 8) agree qualitatively with the experimental data at $Re_D = 8 \times 10^3$–10^4 [Fig. 6(b)]. In these conditions, in the course of simultaneous pneumatic transport of charged and electrically neutral particles, the previous tendency toward the acceleration of dispersed component is replaced, with the charging of the latter, by retardation and hydrodynamic stabilization.

A further decrease in the gas suspension velocity down to $Re_D < 8 \times 10^3$ leads to the predominance of electric forces, acting on the particles, over the hydrodynamic ones and to the manifestation of the specific distributions of hydrodynamic characteristics along the duct length [Fig. 6(a)] that cause a respective configuration of the longitudinal heat transfer coefficient profiles (Fig. 4). The higher effect of Coulombic forces, as compared with the hydrodynamic ones, is favoured by flow laminarization as attested by the experimentally found jump-wise change in the gas suspension friction factor at $Re_D < 8 \times 10^3$. The change in the modes of air flow and heat transfer in a plane duct was studied in work [12] where it was shown that at not very high Reynolds numbers ($Re_D < 2 \times 10^4$), the laminar flow transition into the turbulent one began at a significant distance from the entry section and the

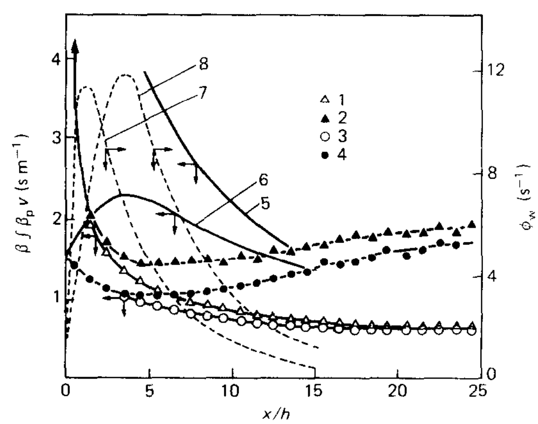

FIG. 8. Longitudinal distributions of the cross-section-averaged volumetric concentrations (1 and 6) and reduced densities of the flow of particles to the duct wall (7 and 8). (1–3) $\bar{E} = 0$; (2, 4–8) $\bar{E} = 7 \times 10^5$ V m^{-1}; (1, 2, 5, 7) $\bar{v}_{sx1|x=0} = 0$; (3, 4, 6, 8) $\bar{v}_{sx1|x=0} = 0.7$ m s^{-1}; (1–4) results of computer experiments; (5, 6) calculation by relation (10); (7, 8) calculation of Φ_w by relations (23) and (17).

transition region was rather large ($x/D > 10$). The turbulent mode of flow develops in the boundary layer actually as soon as Re_D becomes higher than 10^5.

In the conditions of a decreasing effect of turbulent fluctuations of the carrier medium on the motion of particles, the occurrence of local maximum on the profiles of volumetric concentrations and heat transfer coefficients in an electric field [Figs. 6(a) and 4] was considered from the viewpoint of the formation of dipoles on particles during their entry into the interelectrode region and departure from the longitudinal direction as a result of interaction with an inhomogeneous field at the entrance into the test section. The assessment of the interaction between the induced dipole in the system of the electrodes 'semi-plane against plane' and an inhomogeneous electric field shows that the deviation of the particle velocity vector direction from the original one, with the above effect taken into account, does not exceed 3° at $Re_D > 4 \times 10^3$. This testifies to an insignificant effect of the polarization mechanism on the hydrodynamic behaviour of aerosol in the entry sections of the duct.

The formation of the local maximum on longitudinal profiles of concentrations [Fig. 6(a)] due to the replacement of particle retardation by their acceleration is attributed to the fact that an electrically conducting dispersed component enters the section of field effect as having been already charged during pneumatic transport—a fact noted, e.g. in ref. [4]. In this case the cross-section-averaged volumetric concentration of a dispersed component in the section x is comprised of the volumetric concentrations of previously charged and of recharged particles

$$\frac{\bar{\beta}}{\beta_p \bar{v}} = \frac{1}{\beta_p \bar{v}}\left[\frac{1}{\Omega \bar{v}_{sx1}}\left(\frac{G_s}{\rho_s} - Q_x\right) + \frac{Q_x}{\Omega \bar{v}_{sx2}}\right] = \frac{1}{\bar{v}_{sx1}}\left[1 + Q_x^*\left(\frac{\bar{v}_{sx1}}{\bar{v}_{sx2}} - 1\right)\right]. \quad (10)$$

The reduced volumetric flux of previously charged particles at the distance x from the entrance into a plane duct of height h and width b ($\Omega = hb$) is determined by

$$Q_x^* = \frac{Q_x \rho_s}{G_s} = \frac{\rho_s \bar{\beta}|_{x=0} \bar{v}_{sx1}|_{x=0}}{G_s} \times \int_0^x \int_0^h \gamma(q)\left(-\frac{\partial q}{\partial x}\right) b \, dy \, dx = \int_0^\tau \frac{1}{h} \int_0^h \gamma(q)\left(-\frac{\partial q}{\partial \tau}\right) dy \, d\tau, \quad (11)$$

where τ is the time of particle motion before its collision with the wall. For the calculation of the reduced density of the flux of previously charged particles to the electrode

$$\Phi_w = \frac{1}{h}\int_0^h \gamma(q)\left(-\frac{\partial q}{\partial \tau}\right) dy \quad (12)$$

it is necessary to have the dependence of the charge magnitude on the transverse and longitudinal distances traversed by a charged particle prior to its collision with the wall. For this purpose, the equation of the transverse motion of particles in a plane vertical duct was solved

$$m \frac{dv_{sy1}}{d\tau} = qE - k(v_{sy1} - v^a) \quad (13)$$

$$\tau = 0, \quad v_{sy1} = 0, \quad y = 0,$$

from which it was obtained that

$$q = \frac{1}{E}\left[\frac{mBy}{\tau - \frac{1}{B}(1 - e^{-B\tau})} - kv^a\right], \quad (14)$$

$$\frac{\partial q}{\partial \tau} = -\frac{mBy(1 - e^{-B\tau})}{E\left[\tau - \frac{1}{B}(1 - e^{-B\tau})\right]^2}; \quad B = \frac{k}{m}. \quad (15)$$

The differential distribution of particle charges has an exponential form [5]

$$\gamma(q) = \frac{1}{\bar{q}} \exp\left[-\frac{1}{\bar{q}}\left(q + \frac{kv^a}{E}\right)\right] = \frac{1}{\bar{q}} \exp\left\{-\frac{mBy}{\bar{q}E\left[\tau - \frac{1}{B}(1 - e^{-B\tau})\right]}\right\}. \quad (16)$$

With equations (15) and (16) taken into account, the expressions have been obtained for the calculation of the reduced density of particle flux to the wall

$$\Phi_w = \frac{\bar{q}E(1 - e^{-B\tau})}{mBh} \times \left(1 - \left\{1 + \frac{mBh}{\bar{q}E\left[\tau - \frac{1}{B}(1 - e^{-B\tau})\right]}\right\} \times \exp\left\{-\frac{mBh}{\bar{q}E\left[\tau - \frac{1}{B}(1 - e^{-B\tau})\right]}\right\}\right) \quad (17)$$

and reduced volumetric flux

$$Q_x^* = \frac{\bar{q}E}{mBh}\left[\tau - \frac{1}{B}(1 - e^{-B\tau})\right] \times \left(1 - \exp\left\{-\frac{mBh}{\bar{q}E\left[\tau - \frac{1}{B}(1 - e^{-B\tau})\right]}\right\}\right). \quad (18)$$

In the calculation of the volumetric concentrations of a dispersed component by equation (10), the relationship between the time of particle motion and the coordinate x, and also between τ and the velocity $\bar{v}_{sx1}$ was determined from the relations [10]

$$x = (\bar{v} - v_b)\tau + \frac{\bar{v} - \bar{v}_{sx1}|_{x=0} - v_b}{B}(e^{-B\tau} - 1) \quad (19)$$

$$\bar{v}_{sx1} = \bar{v} - v_b - (\bar{v} - \bar{v}_{sx1}|_{x=0} - v_b)e^{-B\tau}. \quad (20)$$

In the case of $\bar{v}_{sx1|x=0} \ll \bar{v} - v_b$, the expressions are simplified to

$$x = (\bar{v} - v_b)\left[\tau - \frac{1}{B}(1 - e^{-B\tau})\right] \quad (21)$$

$$\bar{v}_{sx1} = (\bar{v} - v_b)(1 - e^{-B\tau}) \quad (22)$$

$$\Phi_w = \frac{\bar{q}E\bar{v}_{sx1}}{mBh(\bar{v} - v_b)} \times \left(1 - \left[1 + \frac{mBh(\bar{v} - v_b)}{\bar{q}Ex}\right]\exp\left\{-\frac{mBh(\bar{v} - v_b)}{\bar{q}Ex}\right\}\right) \quad (23)$$

$$Q_x^* = \frac{\bar{q}Ex}{mBh(\bar{v} - v_b)}\left(1 - \exp\left\{-\frac{mBh(\bar{v} - v_b)}{\bar{q}Ex}\right\}\right). \quad (24)$$

Particles, recharged and then accelerated by the air flow, have a velocity given in the following form, similar to equation (22),

$$\bar{v}_{sx2} = (\bar{v} - v_b)(1 - e^{-Ax}) \quad (25)$$

where A determines the length of the acceleration section. Assuming the acceleration section of recharged particles being equal to the section of hydrodynamic stabilization of particles entering the duct, it is possible to obtain

$$A = \frac{B \ln 10}{(\bar{v} - v_b)\ln 10 + 0.9(\bar{v} - v_b - \bar{v}_{sx1|x=0})}. \quad (26)$$

When $\bar{v}_{sx1|x=0} \ll \bar{v} - v_b$,

$$A = \frac{B \ln 10}{(\bar{v} - v_b)(\ln 10 + 0.9)}. \quad (27)$$

The calculation of the hydromechanical characteristics was made for the conditions of the above computer experiment. The mean value of the tribocharge of particles entering the duct ($\bar{q}$) was assumed equal to 1/10 of the value of the inductive charge acquired by particles on having contacted the electrode [9]. The results of calculation of the longitudinal profiles of $\bar{\beta}/\beta_p\bar{v}$, and also of Φ_w are presented in Fig. 8. When $\bar{v}_{sx1|x=0} \ll \bar{v} - v_b$, the tendency toward deceleration of previously charged particles is insignificant as compared with the acceleration of a dispersed component, and the local maximum on the volumetric concentration profiles is absent although the profiles themselves become more flattened. The maximum in the longitudinal distribution of the density of particle flow to the wall at $\bar{v}_{sx1|x=0} \ll \bar{v} - v_b$ is observed in the regions closer to the duct entrance as compared with the case when $\bar{v}_{sx1|x=0}$ is commensurable with $\bar{v} - v_b$ (Fig. 8). In this case, the growth of $\bar{\beta}$ is observed as the main mass of particles is retarded on collision with the wall. After this, when the dispersed component is accelerated by the air flow up to the next collision with the opposite electrode, $\bar{\beta}$ decreases. Subsequently, the dispersed component becomes involved into the ordered interelectrode motion and the concentration of particles increases (Fig. 8).

The described distribution of concentrations with the maximum and minimum corresponds qualitatively to the experimental data obtained for an electrically conducting dispersed material [Figs. 6(a) and 4] generalized by equations (6) and (7) under the conditions of the predominance of transverse electric forces over hydrodynamic ones ($Re_D < 8 \times 10^3$). For a gas suspension with a preliminarily charged dielectric component, the longitudinal volumetric concentration profile 'contains' only a local maximum (Fig. 3). There is no further increase in particle concentration along the channel length because of a much lesser ability of dielectric particles to being recharged as compared with the electrically conducting ones, as a result of which the maximum on the profiles of the local heat transfer coefficients (Fig. 3) is followed by a segment of stabilization.

A characteristic feature of the electric field effect on a charged aerosol (of dielectric or conducting particles) in the transverse direction is an increase of the dispersed component volumetric concentration in the wall regions [4, 5, 13]. For the enhancement of convective heat exchange with a gas-suspension flow, an increase of the volumetric concentration of particles in the electrode zones, together with an increase of its duct cross-section-averaged value, enhances still greater the turbulization of a laminar sublayer which exerts the main thermal resistance to heat transfer to a gas suspension flow [7] and leads to substantial heat transfer enhancement (Fig. 4). For intercomponent processes, an increase of the volumetric concentration of particles in the wall regions, in which the gas velocity is smaller than in the flow core, leads to a substantially nonuniform distribution of water equivalents of the components over the duct cross section and to a decrease in the interphase heat transfer efficiency. The mechanism, which leads to the intercomponent heat transfer enhancement, is an increase in the duct cross-section-averaged volumetric concentrations and relative velocities of particles.

The process of intercomponent heat transfer of a gas suspension in an electric field with allowance for the above competing mechanisms was considered by analysing the system of energy equations of the components

$$\frac{\partial}{\partial x}(\rho c v t) = \frac{6\alpha_s\beta}{d_s}(t_s - t)$$
$$\frac{\partial}{\partial x}(\rho_s c_s v_{s,x}\beta t_s) + \frac{\partial}{\partial y}(\rho_s c_s v_{s,y}\beta t_s) = -\frac{6\alpha_s\beta}{d_s}(t_s - t). \quad (28)$$

The longitudinal nonuniformity in the distribution of the hydrodynamic characteristics of the components exerts negligible effect on the process of intercomponent heat transfer in the absence of a field [14]. Therefore it was assumed that β and $\mathbf{v}_s$ depend only on the transverse coordinate y and are calculated by the formulae for the stabilized segment [10, 13]. The intercomponent heat transfer coefficient was assumed to be constant over the cross-section and was calculated from the mean relative velocity of the components by the relations of ref. [7] in the absence of flow restriction which are also valid for the case of field effect. The field of gas velocities for a turbulent mode of flow was prescribed in the power law form [15].

In the case of the uniform distribution, over the cross-section, of the inlet temperatures of components

$$x = 0,\quad 0 \leqslant y \leqslant h,\quad t = t',\quad t_s = t'_s \tag{29}$$

and disregard of the convective heat transfer, the solution of system (28) is obtained in the form

$$\frac{t}{t'} = 1-\left(1-\frac{t'_s}{t'}\right)\left\{1-\exp\left[-\frac{3\alpha_s h\bar{\beta}}{d_s\rho c\bar{v}}\right.\right.$$
$$\left.\left.\times\left(\frac{c}{c_s\mu}\frac{1}{V^*_{s,x}}+\frac{\beta^*}{V^*}\right)X\right]\right\}\Big/\left(\frac{c}{c_s\mu}\frac{V^*}{V^*_{s,x}\beta^*}+1\right) \tag{30}$$
$$\frac{t_s}{t'_s} = 1+\left(\frac{t'}{t'_s}-1\right)\left\{1-\exp\left[-\frac{3\alpha_s h\bar{\beta}}{d_s\rho c\bar{v}}\right.\right.$$
$$\left.\left.\left(\frac{c}{c_s\mu}\frac{1}{V^*_{s,x}}+\frac{\beta^*}{V^*}\right)X\right]\right\}\Big/\left(1+\frac{c_s\mu}{c}\frac{V^*_{s,x}\beta^*}{V^*}\right)$$

where

$$X = \frac{2x}{h};\quad V^* = \frac{v}{\bar{v}};\quad V^*_{s,x} = \frac{v_{s,x}}{\bar{v}_{s,x}}.$$

On the basis of the relations obtained, the distributions of the cross-section mean mass temperatures of the gas component along the duct length were calculated for the conditions of experimental investigation of intercomponent heat transfer in an electric field (Fig. 9). For comparison, Fig. 9 contains the relations, derived according to the piston flow model ($\beta^* = V^* = V^*_{s,x} = 1$), which describe the effects associated only with an increase in the cross-section-averaged concentrations and relative velocities of a dispersed component. The allowance for the nonuniformity in the distribution of heat-transfer agents in an electric field explains a decrease in the efficiency of intercomponent heat transfer as compared with the piston flow model. Due to this, the electric field effect on the intercomponent processes should be used in those cases when, besides an increase in the cross-section-averaged concentrations and relative velocities of particles, a uniform distribution of components throughout the duct is achieved. As an example, an inclined heat exchanger was considered (Fig. 10), in which, in the absence of an electric field, the heat transfer between a powder ($d_s = 100\ \mu$m, $\rho_s = 5\times10^3$ kg m^{-3}, $c_s = 500$ J K^{-1} kg^{-1}, $\mu = 5$) and a gas ($t' = 150$°C, $\bar{v} = 3$ m s^{-1}) occurs on the boundary of their contact. When the field is switched on, the dispersed material starts to move between the electrodes as a result of which both the cross-section-averaged concentration and the relative velocities of particles increase, and also the uniformity of their distribution throughout the duct is improved which substantially increases the effectiveness of dispersed component heating (Fig. 10). A change in the field strength from zero to the prebreak value allows one to regulate the outlet temperature of the dispersed material.

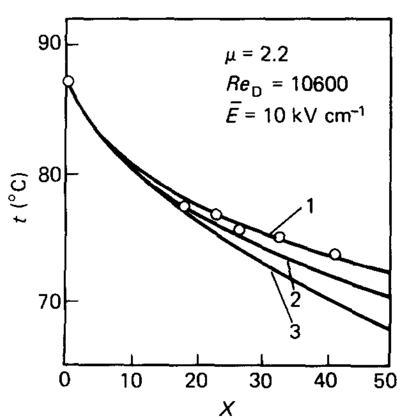

FIG. 9. Distribution, along the length of an intercomponent heat exchanger, of experimental (1) and calculated (2, 3) mean-mass gas temperatures over the cross-section; (2) calculation by relation (30); (3) calculation by the piston flow model.

CONCLUSION

The investigations carried out allow the following conclusions:

(1) The application of an electric field for the enhancement of heat transfer to a gas suspension of dielectric particles is less effective as compared with electrically conducting particles and is expedient in the case of one-sided heat rejection and limited (up to 1 m) duct length.

(2) The specific features of field effect on longitudinal distributions of the local hydromechanical and thermal characteristics of gas-suspended electrically conducting particles are determined by the relationship between the Coulombic and hydrodynamic forces. In the region of the weak effect of electric forces on the hydromechanics of flow ($Re_D > 10^4$), qualitative changes in the structure of an aerosol is not observed. In the case when the Coulombic forces are commensurable with the hydrodynamic ones ($8\times10^3 < Re_D < 10^4$), a relative quantity of charged particles, involved in interelectrode motion, increases and this leads to the appearance of the heat transfer minimum over the segment of stabilization. The predominance of electric forces over the hydrodynamic ones in the conditions of flow laminarization, $Re_D < 8\times10^3$, leads to the formation, over the heat exchanger starting length, of the local heat transfer maximum due to the interaction of previously charged particles with the electric field. The field effect on heat transfer to a gas suspension in the region with $Re_D < 8\times10^3$ is the most significant and is described by the equations derived.

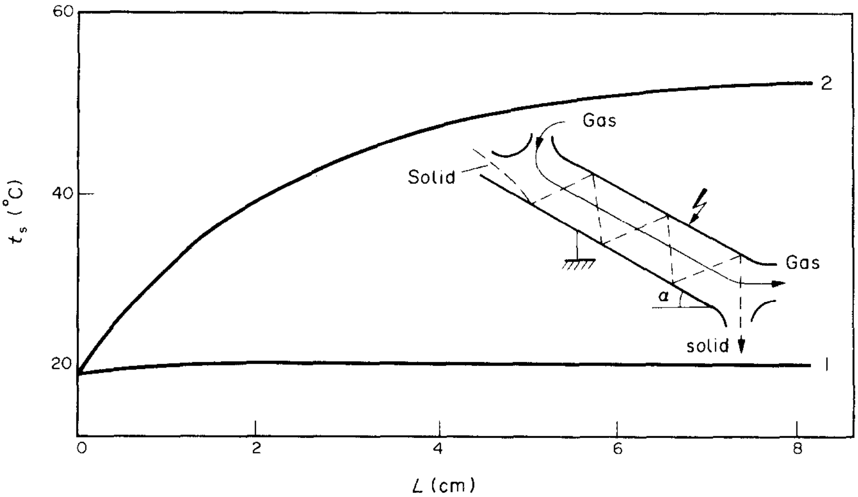

FIG. 10. Dependence of the dispersed component temperature (d_s = 10^{-4} m) on the heat exchanger length (1, 2) $\bar{E} = 0$; 10^6 V m^{-1}.

(3) It has been established experimentally that an electric field does not influence the intensity of intercomponent heat transfer. The effectiveness of the field action on dispersed material heating in a gas suspension flow is associated with the competing interaction of two mechanisms: an increase in the duct cross-section-averaged concentrations and relative velocities of particles and an increase of the nonuniform distribution of components in the transverse direction under the field effect. The enhancement of heat transfer to a dispersed material in a field is expedient in those cases when the latter mechanism also improves the conditions of the hydrodynamic interaction of components.

(4) The enhancement of heat transfer of gas-disperse systems with the aid of an electric field allows one to reduce the dimensions of heat exchangers and to control the heat release from heat transfer surfaces and heating of a dispersed material.

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ACCROISSEMENT DU TRANSFERT THERMIQUE INDUIT PAR UN CHAMP ELECTRIQUE DANS UN ECHANGEUR DE CHALEUR A SUSPENSION GAZ–SOLIDE

Résumé—On étudie le transfert de chaleur et l'hydrodynamique des écoulements de gaz avec suspension, sous l'action d'un champ électrique transversal. On conduit une analyse des comportements spécifiques d'un écoulement aérosol avec différentes relations entre les forces électriques et hydrodynamiques qui agissent sur les particules. On identifie les conditions qui correspondent à l'utilisation d'un champ électrique au maximum d'efficacité pour l'accroissement du transfert thermique dans les écoulements de gaz avec suspension.

VERBESSERUNG DER WÄRMEÜBERTRAGUNG IN EINEM WÄRMETAUSCHER MIT EINER GAS–FESTSTOFF-SUSPENSION IN ANWESENHEIT EINES ELEKTRISCHEN FELDES

Zusammenfassung—Die Arbeit behandelt die Untersuchung von Wärmetransport und Hydromechanik von gasdispersen Strömungen unter dem Einfluß eines querverlaufenden elektrischen Feldes. Die besonderen Merkmale einer Aerosolströmung wurden bei unterschiedlichen Verhältnissen von elektromagnetischen und hydrodynamischen Kräften untersucht. Diejenigen Zustände wurden ermittelt, bei denen die Zuschaltung eines elektrischen Feldes bei größtmöglichem Wirkungsgrad den Wärmeübergang sowohl an gasdurchsetzte Teilchenströme als auch zwischen den Komponenten erhöht.

ИНТЕНСИФИКАЦИЯ ТЕПЛООБМЕНА В ГАЗОДИСПЕРСНОМ ТЕПЛООБМЕННИКЕ ПОД ВОЗДЕЙСТВИЕМ ЭЛЕКТРИЧЕСКОГО ПОЛЯ

Аннотация—Исследованы теплообмен и гидромеханика газодисперсных потоков под воздействием поперечного электрического поля. Проведен анализ особенностей течения аэрозоля при различных соотношениях электрических и гидродинамических сил, действующих на частицы. Определены условия, обеспечивающие максимальную эффективность использования поля для интенсификации теплопереноса к потокам газовзвеси и межкомпонентного теплообмена.