FLOW OF A FINE-DISPERSED HETEROGENEOUS MEDIUM IN A TURNING CHANNEL OF A GAS DUCT

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Results of a numerical study of turbulent flow of a polydispersed two-phase mixture in a turning section of a gas duct are presented. Calculated data allow a localization of the zone of particle accumulation at the channel walls and an evaluation of efficiency of the particle entrapment in a hopper.

An up-to-date level of the development of hydrodynamics, mechanics of turbulent flows, and computing machinery offers hope for obtaining a concrete result in solving, by numerical modeling, the engineering problems involving a design of new devices in power engineering and chemical technology, as well as an improvement of their operational conditions. Numerical modeling acquires particular significance in studying flows whose reproduction in the laboratory is difficult or entirely impossible. A case in point may be aerodynamic processes occurring in boiler plants, the results of whose investigation using physical models are far from being always applicable to full-scale objects because of the so-called "scale effect." Numerical models are devoid of this shortcoming. However, they are tested and supported by the results of experimental studies, mostly performed under laboratory conditions. From this standpoint, the flows in laboratory setups, just as in the full-scale aerodynamic process, appear highly important.

The current work is concerned with modeling a polydispersed flow in a turning channel of the physical model of a boiler plant gas duct. The ultimate goal of the study is to numerically obtain the aerodynamic pattern of the flow in the turning gas-air channel in the initial geometry, to investigate the effect of a turn angle of the gas duct outlet branch on the efficiency of particle entrapment in the hopper, and to localize the zones of increased particle content in near-wall regions of the gas duct.

A mathematical model of the considered process is based on the chief postulates of the theory of interacting interpenetrating continua [1]. Polydispersity is taken into account through isolating main fractions by the function, which defines a granulometric composition of the dispersed phase. It is assumed that the particles of each phase are of spherical shape and of the same size; the density of the particle material greatly exceeds the density of the carrying medium, the volume concentration of the particles is small, and their collisions may be disregarded.

Equations defining a plane steady turbulent flow of the two-phase polyfractional medium have the form:

\[
\begin{align*}
\frac{\partial}{\partial x} (\rho_i U_i) &+ \frac{\partial}{\partial y} (\rho_i V_i) = 0, \\
\frac{\partial}{\partial x} (\rho_i U_i U_i) &+ \frac{\partial}{\partial y} (\rho_i U_i V_i) = \\
&= -\alpha_i \frac{\partial}{\partial x} \left( \frac{2}{3} \frac{\partial}{\partial x} (\rho_i K) \right) I_{il} + 2 \frac{\partial}{\partial x} \left( \mu_i \frac{\partial U_i}{\partial x} \right) + \\
&+ \frac{\partial}{\partial y} \left( \mu_i \frac{\partial U_i}{\partial y} \right) + \frac{\partial}{\partial y} \left( \mu_i \frac{\partial V_i}{\partial y} \right) + F_{xi i} - \nu_i g, \\
\frac{\partial}{\partial x} (\rho_i U_i V_i) &+ \frac{\partial}{\partial y} (\rho_i V_i V_i) = -\alpha_i \frac{\partial}{\partial y} \left( \frac{2}{3} \frac{\partial}{\partial y} (\rho_i K) \right) I_{il} + \\
&+ \frac{\partial}{\partial x} \left( \mu_i \frac{\partial V_i}{\partial x} \right) + 2 \frac{\partial}{\partial y} \left( \mu_i \frac{\partial V_i}{\partial y} \right) + \frac{\partial}{\partial x} \left( \mu_i \frac{\partial U_i}{\partial x} \right) + F_{yi i}, \\
\frac{\partial}{\partial x} (\rho_i U_i T_i) &+ \frac{\partial}{\partial y} (\rho_i V_i T_i) = Q_i + \\
&+ \frac{\partial}{\partial x} \left( \mu_i \frac{T_i}{\sigma_{hi}} \frac{\partial T_i}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu_i \frac{T_i}{\sigma_{hi}} \frac{\partial T_i}{\partial y} \right), \quad P = \rho_i RT_i.
\end{align*}
\]
Dynamic and thermal interactions between the phases are determined by the following relations:

\[ F_{xi} = \rho_i \frac{f_{Di}}{\tau_{pi}} (U_i - U_i), \quad F_{yi} = \rho_i \frac{f_{Di}}{\tau_{pi}} (V_i - V_i), \]

\[ \tau_{pi} = 1 + 0.15 \text{Re}_{i0.67}, \]

\[ \text{Re}_{i} = \rho_i d_{pi} [(U_i - U_i)^2 + (V_i - V_i)^2]^{0.5}/\mu_i, \quad i > 1, \]

\[ F_{xi} = -\sum_{i=2}^{m} F_{xi}, \quad F_{yi} = -\sum_{i=2}^{m} F_{yi}, \quad Q_i = \frac{6 \lambda_i \sigma_i \text{Nu}_i}{C_i d_{pi}}, \]

\[ \text{Nu}_i = 2 + 0.459 \text{Re}_{i0.55} \text{Pr}_{0.33}, \quad i > 1, \]

where \( \mu_1 \) and \( \lambda_1 \) are the viscosity and thermal conductivity coefficients of the carrying medium, and \( C_i \) (\( i = 1, \ldots, m \)) is the specific heat of unit mass of the gas or particle fraction.

Presently, the transport models which take into consideration differential equations for averaged turbulence characteristics are widely used in modeling the processes of turbulent transfer. The application of such models is indispensable in the cases when the flow is associated with separation, chemical transformations, and with the effect of a heterogeneous phase on the averaged flow and turbulent transfer processes. Such models are essentially semiempirical, however, they are appreciably more potent for taking account of the influence of physical mechanisms complicating the flow.

The current study predicts a turbulent structure of the flow from the two-equation \( k-e \) turbulence model, modified in [2] to allow for the effect of the dispersed phase on averaged turbulence characteristics:

\[ \frac{\partial}{\partial x} (\rho_i U_i K) + \frac{\partial}{\partial y} (\rho_i V_i K) = \frac{\partial}{\partial x} \left( \frac{\mu_{11}}{\sigma_i} \frac{\partial K}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\mu_{11}}{\sigma_i} \frac{\partial K}{\partial y} \right) + \mu_{11} G - \rho_i e + S_K, \]

\[ \frac{\partial}{\partial x} (\rho_i \phi) + \frac{\partial}{\partial y} (\rho_i \phi) = \frac{\partial}{\partial x} \left( \frac{\mu_{11}}{\sigma_e} \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\mu_{11}}{\sigma_e} \frac{\partial \phi}{\partial y} \right) + \frac{\mu_{11}}{\sigma_e} \frac{\partial \phi}{\partial y} + \frac{\mu_{11}}{\sigma_e} \frac{\partial \phi}{\partial x} + \frac{\mu_{11}}{\sigma_e} \frac{\partial \phi}{\partial y}, \]

Here \( G = \left( \frac{\partial U_i}{\partial x} + \frac{\partial V_i}{\partial y} \right)^2 + 2 \left( \frac{\partial U_i}{\partial x} \right)^2 + 2 \left( \frac{\partial V_i}{\partial y} \right)^2 \) is the dissipative function; \( T_L = 5K/(12\epsilon) \) is the local Lagrangian time scale; \( S_K \) and \( S_e \) are the terms taking into account the particle effect on turbulence [2]:

\[ S_K = -2K \sum_{i=2}^{m} \frac{\rho_i}{\tau_{pi} + T_L}, \]

\[ S_e = -2S \sum_{i=2}^{m} \frac{\rho_i}{\tau_{pi} + T_L} + 2 \frac{\mu_{11}}{\rho_i} \frac{\partial K}{\partial x} \frac{\partial T_L}{\partial x} + 2 \frac{\partial K}{\partial y} \frac{\partial T_L}{\partial y} \sum_{i=2}^{m} \frac{\rho_i}{\tau_{pi} + T_L^2}. \]

To obtain a turbulent viscosity coefficient for the particle continuum we use the Peskin equation:

\[ \frac{\mu_{11}}{\mu_{11}} = \frac{\rho_i}{\rho_1} \left[ 1 - 1.5 \left( \frac{L}{H} \right)^2 \frac{\Omega_i^2}{\Omega_i^2 + 2} \right], \quad i = 2, m, \]

where \( L \) is the turbulence scale, \( \Omega_i = 2 \tau_{pi}/T_L \) is the relaxation parameter, and \( H \) is the characteristic geometric scale.

The turbulence model constants fit the standard values: \( c_1 = 1.44, c_2 = 1.92, c_{11} = 0.09, c_K = 1, \) and \( c_e = 1.3. \)