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Local flow structure during injection of a radial annular gas-droplet jet into a cross-cross turbulent gas flow

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Received April 10, 2025
Revised May 3, 2025
Accepted May 3, 2025

A numerical analysis of the flow structure and thermal efficiency of a gas-droplet jet injected through a radial annular slot into a transverse single-phase air flow is performed. The calculations are performed using the axisymmetric RANS approach in the following range of variation of the main parameters of the two-phase flow. Gas turbulence is described using the Reynolds stress component transfer model recorded taking into account the two-phase flow. An increase in the blowing ratio in the range of $m = 0.5-4$ causes a significant increase in the separation region length by almost 3 times. An increase in the blowing ratio leads to an increase in the friction coefficient.

Keywords: RANS, numerical modeling, Reynolds stress transport model, turbulence, radial slot gas-droplet jet, transverse flow, pipe, flow structure.

DOI: 10.61011/TPL.2025.08.61534.20341

Injection of radial annular or slot jets into a cross gas flow in a pipe (or a channel) is often used to intensify the mixing process in combustion chambers of power plants. Although such injection is easy to implement, this method of thermal protection has a rather complex flow hydrodynamics, even in the case of injection of a single-phase coolant flow through an opening normally into a cross flow in a channel [1–3]. When a radial jet is injected normally into a transverse gas flow, a separation flow region is formed behind the obstacle in the form of the jet itself. Therefore, the study of the mixing process, the dynamics of flow development, and the loss of total pressure during the injection of a radial annular jet normal to the axis of the primary turbulent flow is of academic and practical importance. Note that most studies are focused on the process of jet injection through single openings of various shapes or slots into a flat channel in the isothermal case [1–3]. The heat transfer between a single-phase jet injected through a circular opening or a flat slot into a transverse flow in a flat channel was investigated experimentally in [4–6].

The process of mixing and heat transfer in the case of injection through an annular slot into a pipe differs significantly from injection through an opening into a flat channel with a transverse flow. This case is significantly less investigated, and only the single-phase flow regime was discussed in literature [7]. Measurements of the local structure and the distribution of static and dynamic pressures and hydraulic resistance were carried out in this study, and an engineering method for calculating hydraulic resistance in the isothermal injection case was developed.

It is known that the addition of evaporating droplets to a gas flow causes a significant (in certain cases, several-fold) intensification of heat transfer in comparison with a single-phase flow [8,9]. We know of only one study [10] into the injection of a gas-droplet coolant flow through an annular slot into a transverse heated flow. The present work is a continuation of [10], where the thermal efficiency in the case of injection of a radial gas-droplet jet into a turbulent air flow in a pipe was modeled. The aim of the present study is to examine numerically the local structure during injection of an annular gas-droplet jet into a turbulent transverse single-phase flow of heated air (Fig. 1).

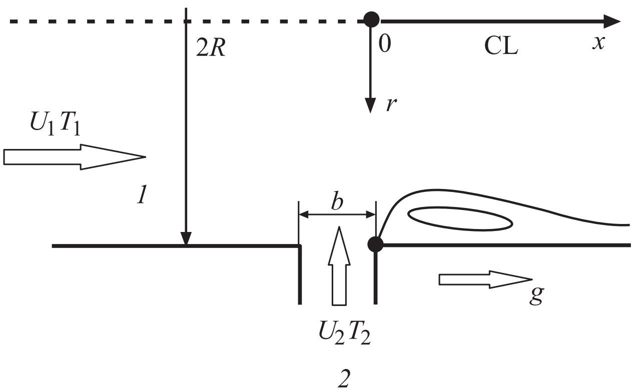

Figure 1. Diagram of development of a wall gas-droplet jet injected through an annular slot along the normal to the primary flow (not to scale). *1* — Primary flow of single-phase heated gas, *2* — secondary annular gas-droplet coolant flow; CL — axis of symmetry of the pipe.

This problem is solved using axisymmetric stationary RANS-equations written with account for the influence of evaporating droplets on transfer processes in gas [10]. The Eulerian continuum approach is used to characterize the dynamics of flow and heat-and-mass transfer in gas

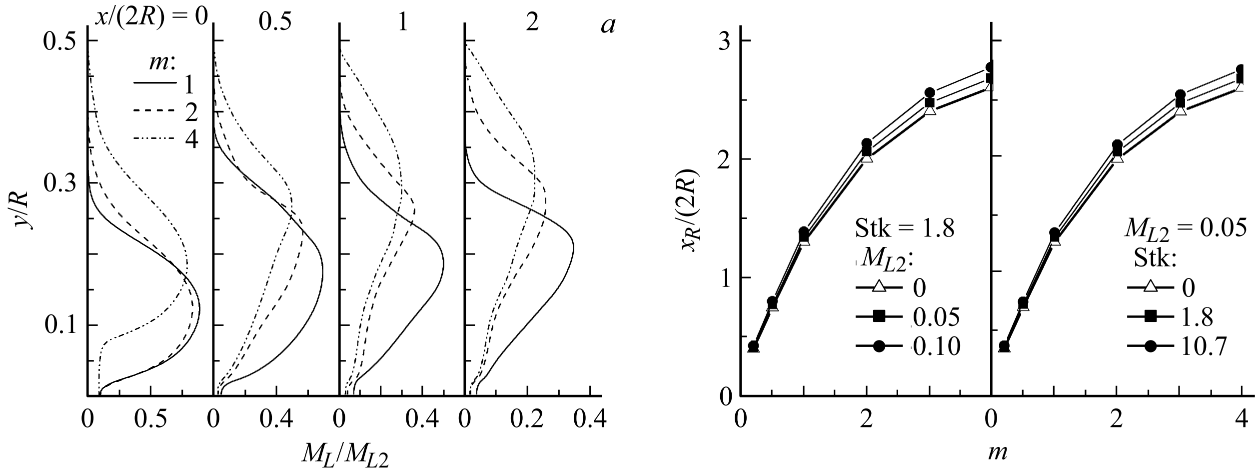

Figure 2. Influence of the injection ratio on droplet concentration profiles ($d_2 = 20\,\mu$m, Stk = 1.8, $M_{L2} = 0.05$) (a) and influence of the added disperse phase on extent of the flow recirculation zone (b).

and disperse phases. Turbulence of the carrier phase was characterized within the elliptical model of transport of Reynolds stresses [11] with account for the two-phase nature of the flow [10]. The schematic flow diagram is presented in Fig. 1. The volume concentration of droplets in the secondary flow is low ($\Phi_2 = M_{L2}\rho_2/\rho_{L2} \leq 1.2 \cdot 10^{-4}$), and they are rather small (initial diameter $d_2 = 10{-}50\,\mu$m). Here, M_{L2} is the initial mass concentration of droplets and ρ_2 and ρ_{L2} are the gas and droplet densities; therefore, the fragmentation and coalescence of droplets in the flow are neglected [8,10].

All numerical calculations were performed for a mixture of air with water droplets in the case of injection of a radial annular two-phase jet into a pipe with vertical downward motion of a single-phase air flow at atmospheric pressure (Fig. 1). The pipe diameter was $2R = 100$ mm, and the width of the annular slot was $b = 5$ mm ($b/R = 0.1$). The computational domain is a section with a length of $(-5{-}30)R$ for the main cylindrical channel; the length of the computational block of the feed pipe for the secondary flow was $(-2.5{-}0)R$. The average-flow-rate velocity of gas (air) in the inlet section was $U_1 = 15$ m/s, and the velocity of the secondary flow (air and water droplets) varied within the range of $U_2 = 6{-}47.5$ m/s. The injection ratio was varied within a wide range: $m = \rho_2 U_2/(\rho_1 U_1) = 0.5{-}4$. The Reynolds numbers for the gas phase derived from the parameters of the primary and secondary flows were $\mathrm{Re}_1 = U_1 2R/\nu_1 = 6.5 \cdot 10^4$ and $\mathrm{Re}_2 = U_2 b/\nu_2 = (0.2{-}1.6) \cdot 10^4$, where subscripts 1 and 2 correspond to the primary and secondary flows and ν is the kinematic viscosity coefficient. Stokes number of averaged motion $\mathrm{Stk} = \tau/\tau_f = 0.5{-}10.7$ is a parameter characterizing the behavior of particles in a flow. It is the ratio of dynamic relaxation time $\tau = \rho_{L2} d_2^2/(18\mu_2 W)$ determined with account for the deviation from the Stokes flow law to characteristic turbulent temporal macroscale τ_f ($\tau_f = b/U_2$ is the turbulent temporal macroscale calculated based on the secondary flow parameters). Here, μ is the dynamic viscosity of the carrier flow, $W = 1 + 0.15\mathrm{Re}_L^{0.687}$, $\mathrm{Re}_L = |\mathbf{U}_{S2} - \mathbf{U}_{L2}| d_2/\nu_2$ is the Reynlods number of the disperse phase, and $\mathbf{U}_{S2}$ and $\mathbf{U}_{L2}$ are the averaged velocity vectors of the gas phase at the position of the droplet and the disperse phase, respectively.

The temperatures of phases in the secondary two-phase flow in the inlet section were constant $T_{L2} = T_2 = 293$ K, and the mass concentrations of water droplets and water vapor were $M_{L2} = 1{-}10\,\%$ and $M_{V2} = 0.01\,\%$ at an initial diameter of water droplets of $d_2 = 10{-}50\,\mu$m. The temperature of the primary air flow was $T_1 = 373$ K. The pipe wall was thermally insulated, and droplets from the two-phase turbulent flow could settle on it. The process of droplet deposition was taken into account simply by reducing their number in the next calculated section. Just as in [8,10], a liquid film did not form on the wall.

A numerical solution was obtained by the finite volume method on staggered grids using a proprietary numerical code. The QUICK procedure of the third order of accuracy was used for convective terms of differential equations, and central differences of the second order of accuracy were used for diffusion flows. The pressure field was corrected in accordance with the SIMPLEC procedure. The grid was non-uniform and was refined toward the pipe wall and the injection section. All calculations were performed on the grid containing 400×100 (in axial and radial directions) control volumes (CVs) in the main cylindrical channel and 25×100 CVs in the feed annular channel for the secondary flow. A further increase in CV number had no significant effect on the results of numerical calculations.

The profiles of mass concentration of droplets at different values of the injection ratio are presented in Fig. 2, a. The concentration of the disperse phase decreases as droplets evaporate and mix with the primary flow. Its value in the core of the primary flow is $M_L/M_{L2} \approx 0$ at moderate injection ratios ($m \leq 2$). An increase in

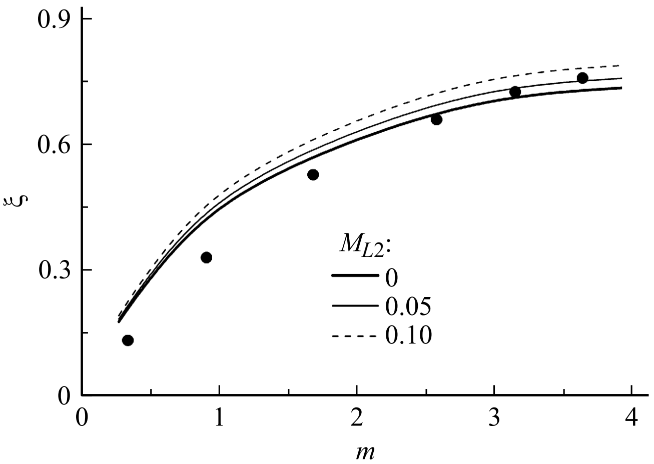

Figure 3. Variation of friction coefficient ξ during injection of radial annular single- and two-phase gas-droplet jets with injection ratio. Dots and curves represent the measurement data from [7] and the results of our calculations, respectively. The measurement conditions were as follows [7]: $b = 2.2$ mm, $G_2 = \rho_2 U_2 b = 22$ g/s, $2R = 34$ mm, and $\mathrm{Re}_1 = 5.5 \cdot 10^4$.

injection ratio leads to an increase in depth of penetration of the annular normal two-phase jet into the transverse single-phase air flow. Consequently, the position of the maximum concentration of the disperse phase also shifts slightly toward the pipe axis. One of the most important integral parameters for separated flows is their length. The influence of the mass concentration of droplets and their initial diameter on this parameter at $\mathrm{Stk} = 0-10.7$ is presented in Fig. 2, *b*. Note also that single- and two-phase flows have virtually the same recirculation region length (the difference reaches 6% at $M_{L2} = 0.1$). The variation of main parameters of the disperse phase within the examined range has virtually no effect on the length of the separation zone. In contrast, as the injection ratio increases from $m = 0.5$ to $m = 4$, the separation region undergoes a significant (almost 3-fold) extension: from $x_R \approx 1.5R$ to $x_R \approx 5.2R$. Additional calculations for an isothermal gas-droplet flow were carried out in order to identify the effect of mass transfer due to droplet evaporation on the local flow structure during injection of a radial two-phase jet into the primary gas flow. It was found by analyzing the profiles of averaged axial gas velocity that this influence is insignificant and does not exceed 4%.

Calculated data on friction coefficient ξ, $\xi = 2 \times \times (P_1 - P_{1,out})/(\rho_{1,out} U^2_{m1,out})$, in the case of injection of a radial annular gas-droplet jet into the primary air flow are shown in Fig. 3. Here, P_1 and $P_{1,out} = P^{st}_{1,out} + \rho_{1,out} U^2_{m1,out}/2$ are the total pressures on the axis at the channel inlet and outlet, respectively. The data are presented in the form of dependences of coefficient ξ on injection ratio m. It can be seen that the friction coefficient increases with injection ratio, and the data on ξ during injection of a two-phase radial annular jet into the primary cross gas flow depend only weakly on injection ratio m at high values of this ratio ($m > 3$). Note that the comparison with experimental data is mostly qualitative, since the conditions set in [7] differ significantly from the conditions of the present calculations.

Funding

This study was supported financially by a mega-grant from the Ministry of Science and Higher Education of the Russian Federation (agreement No. 075-15-2024-620).

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin