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The effect of flow swirling on flow structure, turbulence and heat transfer in turbulent droplet-laden flow in a pipe sudden expansion

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Abstract. This paper presents the mathematical model to simulate the swirling turbulent gas-droplet flow in a sudden pipe expansion. The set of axisymmetrical steady-state RANS equations for the two-phase flow is used. The dispersed phase is modeled by the Eulerian approach. The flow swirl causes an increase in the intensity of heat transfer (more than 1.5 times in comparison with the non-swirling mist flow at other identical inlet conditions). Evaporation of the droplets leads to a significant increase in the heat transfer intensity in the swirling two-phase flow (more than 2.5 times in comparison with the single-phase flow). It is shown that ethanol droplets evaporate much faster than water droplets due to the lower heat of phase transition. The heat transfer enhancement by using ethanol droplets is higher than the corresponding value for water droplets (up to 20%).

Introduction
Two-phase flows with solid or liquid particles with separation, swirling and rotation are frequently encountered flow phenomena in various practical applications: gas and coal combustor chambers, flow in turbomachinery parts, centrifugal separators, etc. Turbulent one-phase swirling flows through sudden expansion are characterized by high local gradients of the mean and fluctuational parameters, high level of turbulence, one or two recirculation zones due to the action of centrifugal and Coriolis forces [1,2]. Interaction between the particles and gas phase turbulence is a very complex process. Evaporation of the droplets is one of the ways to achieve significant enhancement of heat transfer [3,4]. The latent heat of evaporation is the key parameter that affects the enhancement of the heat transfer rate by using gas-droplet mist flows. The presence of flow recirculation and swirling affects the intensity of momentum, heat, and mass transfer and strongly determines the structure of the turbulent flow [1,2]. Therefore, despite a widespread use of two-phase swirling flows in various practical applications, the processes of turbulent mixing and transport in such flows remain insufficiently studied.

It should be noted that the studies of two-phase swirling flow under the conditions close to real internal flows in the combustion chambers have been carried out so far. However, the effect of such important parameters as the droplets inlet diameter, their mass fraction and swirl number on the transport of momentum, heat and mass remains almost uninvestigated. This study may be of interest to the scientists and engineers dealing with the enhancement of the heat transfer rate in power equipment.
The paper does not have direct practical application and it shows one of the ways to control heat transfer enhancement in the two-phase flow with droplets evaporation and swirling. Potential applications, where high heat fluxes should be removed while the surface is kept at a relatively low temperature, include high-power equipment, etc.

The aim of the present study is to examine numerically the effect of the thermophysical properties of droplets and swirl number on flow, turbulence and heat transfer in a two-phase mist swirling flow in a pipe with sudden expansion. The current study is a continuation of [5], where the SMC model was applied to describe the gas-droplet swirling flow downstream a sudden pipe expansion. The paper is organized as follows. In Section 2, the governing equations and numerical method employed in this study for simulation of two-phase mist swirling flow are introduced. The numerical study of the droplet-laden swirling flow and results of comparative analysis is presented in Section 3. The last part summarizes the main findings and conclusions.

1. Mathematical model

1.1. Governing equations

The dispersed phase is modeled by the Eulerian approach [6,7], which treats the dispersed phase (droplets) as a continuous medium with properties analogous to those of a fluid. This technique involves the solution of a second set of Navier–Stokes-like equations in addition to those of the carrier (gas) phase. Properties such as the mass of particles per a unit volume are considered as a continuous property and the droplet velocity is the averaged velocity over an averaging control volume. Also, the interfacial transfer of mass, momentum and energy requires averaging over the computational control volume. The droplets behavior in turbulent fluid and their back action on the flow is determined by drag, gravity force, turbulent transport and turbulent diffusion. In order to account for the interaction between phases, i.e., momentum exchange and heat and mass transfer, the conservation equations have to be extended by appropriate source/sink terms [5].

In the present paper, the dilute droplet-laden swirling flow downstream a sudden pipe expansion is numerically examined. The volume concentration of the dispersed phase is assumed to be lower than (\(\Phi_1 < 10^{-5}\)) and sufficiently fine (\(d_1 < 100 \mu m\)); therefore, the effects of inter-particle collisions are neglected when treating the hydrodynamic and heat and mass transfer processes in the two-phase flow. All computations are performed for monodisperse gas-droplet flow at the inlet cross-section at a uniform wall temperature \(T_w = 373\) K. Then the size of the droplets changes in all directions due to their evaporation. The droplet is the sink of heat and source of vapor. The mass fraction of droplets decreases steadily in the downstream direction due to evaporation, sudden pipe expansion and their deposition onto the solid wall surface.

The system of RANS equations, second moment closure transport equations and equation of dissipation rate, and mean and fluctuational transport equations for the dispersed phase have the form of [5].

1.2. Numerical implementation

The mean transport equations for both gas and dispersed phases and SMC model are solved using the control volumes method on a staggered grid. The QUICK scheme is used to approximate the convective terms, and the second-order accurate central difference scheme is adopted for the diffusion terms. The velocity correction is used to satisfy continuity through the SIMPLEC algorithm, which couples velocity and pressure.

The results of preliminary calculations for the single-phase flow in a pipe with the length of 150\(R\) are used for the gas-phase velocity and turbulence on the pipe edge. These conditions are sufficient to achieve fully developed turbulent gas flow. The symmetry conditions are set on the pipe axis for gas and dispersed phases. No-slip conditions are set on the wall surface for the gas phase. Boundary conditions on the wall surface for the dispersed phase correspond to the conditions of an “absorbing surface” [9], under which the droplets do not return to the flow after making contact with the solid
wall. After their deposition onto the pipe surface, the droplets are assumed to be momentarily vaporised [5]. At the outlet edge, computational domain condition $\partial \phi / \partial r = 0$ is set for all variables. The first cell is located at distance $y_+ = y U_s / \nu = 0.3–0.5$ from the wall, where $U_s$ is the friction velocity obtained for the gas flow in the inlet pipe. At least 10 control volumes have been generated to be able to resolve the mean velocity field and turbulence quantities in the viscosity-affected near-wall region ($y_+ < 10$). Grid sensitivity studies are carried out to determine the optimum grid resolution that gives the mesh-independent solution. For all numerical investigations performed in the study, a basic grid with $256 \times 80 \times 80 \approx 1.64 \text{ Mio}$ control volumes is used. Grid convergence is verified for three grid sizes: $128 \times 40 \times 40$, and $400 \times 160 \times 160$ control volumes. A more refined grid is applied in the recirculation region and in the zones of flow detachment and reattachment.

**Numerical results and their discussion**

The swirling two-phase gas-droplet flow is studied in the downward flow regime downstream sudden pipe expansion. The computational domain is schematically presented in Figure 1. The main jet of the mixture of air and water droplets (1) is supplied into the central channel ($2R_1$). The swirling single-phase gas flow (2) arrives through the annular channel ($R_3 - R_2$). The computational domain geometry is as follows: $2R_1 = 20 \text{ mm}$, $2R_2 = 26 \text{ mm}$, $2R_3 = 40 \text{ mm}$, $2R_4 = 100 \text{ mm}$, and the step height is $H = 30 \text{ mm}$. The computational domain length is $X = 1 \text{ m}$. The mean mass axial velocity of the main air flow $U_{m1} = 15 \text{ m/s}$ and its mass flow rate is $G_1 = 22.6 \text{ g/s}$. The mass flow rate of air in the secondary annular jet is $G_2 = 18 \text{ g/s}$. The flow swirl number varies within $S = \left( \int_0^{R_1} \rho U_r W r^2 dr \right) / \left( \int_0^{R_1} \rho U_\gamma^2 r dr \right) = 0 – 1$. The gas-phase Reynolds number is $Re = U_m 2R_1 / \nu = 2 \times 10^4$. The initial mean axial droplet velocity is $U_{d1} = 12 \text{ m/s}$. The initial water droplet diameter is $d_1 = 10–100 \mu \text{m}$ and their mass concentration varies within $M_{d1} = 0–0.1$. The particle relaxation time is $\tau = \rho_s d_1^2 / (18 \mu W) = 0.3–30 \text{ ms}$, where $W = 1 + \text{Re}_L^{2/3} / 6$, where $\text{Re}_L = |U - U_L| d_1 / \nu$ is the Reynolds number for the dispersed phase. The wall temperature is constant along the whole length of the computation domain at $T_w = 373 \text{ K}$. The gas and droplet temperature at the initial cross-section is $T_1 = T_{d1} = 293 \text{ K}$.

**Figure 2** shows the radial profiles of the mean axial (a) and tangential (b) gas-phase velocities at several stations along the pipe length ($x/H = 2–15$) for various swirling numbers. Bold lines (I) are the predicted values for the gas phase in two-phase flow without swirling ($S = 0$). The addition of flow swirling has a strong effect on the mean flow structure (see figure 2). All predicted profiles of the axial gas velocity have the maxima, whose position shifts toward the pipe wall in the downstream direction, except for the first section. Similar deformations occur with a tangential velocity of gas and in the outlet section they are close to each other and rearranged according to the law of solid body rotation [1] (see figure 2b). An increase in flow swirling number $S$ leads to increasing tangential velocity of the gas phase.
Figure 2. The effect of flow swirling on distributions of mean axial (a) and tangential (b) components of the gas phase velocities in droplet-laden flow.

Re = \(2 \times 10^4\), \(d_1 = 30\ \mu m\), \(M_{L1} = 0.05\), water droplets.

1 – S = 0 (non-swirling flow), 2 – 0.25, 3 – 0.5.

Figure 3. The distribution of normalized volume fraction of water (solid curves) and ethanol (dashed lines) droplets along the pipe axis. Re = \(2 \times 10^4\), \(d_1 = 30\ \mu m\), \(M_{L1} = 0.05\). 1 – S = 0 (non-swirling flow), 2 – 0.25, 3 – 0.5.

The axial distributions of droplets volume fraction along the pipe length for various swirling numbers are shown in figure 3. Here, \(\Phi_0\) are \(\Phi_1\) are the volume concentrations of particles on the pipe axis and in the inlet, respectively. The rapid scattering of droplets over the cross-section of the pipe is observed for a two-phase separated flow without swirling (lines 1, S = 0). It causes a sharp decrease in the volume fraction in the axial zone of the pipe. For a swirling flow, accumulation of particles on the
axis is characteristic due to the action of centrifugal and turbophoresis forces. This effect becomes more pronounced with an increase in the swirling number, which agrees with the results of [10] for a swirling confined two-phase flow with solid particles downstream a pipe sudden expansion. Further, volume concentration of droplets in the near-axis region decreases sharply and $\Phi_0 \approx 0$ at a large distance ($x/H > 25$). The ethanol droplets evaporate faster than water droplets and values of volume fraction of ethanol droplets are lower than those for water droplets.

The effect of adding droplets on a change in the maximum value of heat transfer in the swirling flow in the sudden pipe expansion is shown in figure 4. Here, $ER_{max} = (Nu/g/Nu_{8,0})_{max}$, where $Nu_g$ and $Nu_{8,0}$ are the maximal Nusselt numbers in the gas-droplet swirling flow and single-phase swirling flow ($M_{t,1} = 0$), respectively. Evaporation of droplets leads to a significant increase in the heat transfer intensity in the swirling two-phase flow (more than 2 times in comparison with the single-phase flow with other identical parameters). This is due to a more intense mixing process and turbulence generation in the near-wall region of the pipe. This effect increases with the increasing mass fraction of droplets. Initially, there is a sharp augmentation of heat transfer with increasing inlet mass fraction of particles. The magnitude of maximal heat transfer enhancement is higher for ethanol droplets than for water droplets.

**Comparison with experimental results**

The results of experiments of [11] and LES simulations of [12] are used for comparative analysis. The swirling two-phase flow of air and kerosene droplets is studied in a horizontal flow downstream a sudden channel expansion. The height of the square channel was 130 mm, its length was 245 mm, and step height was $H = 50$ mm. The diameter of nozzle for kerosene supply was $2R_1 = 5$ mm and diameter of the peripheral hole for air supply was $2R_3 = 30$ mm. The gas and droplet temperatures at the inlet were $T_1 = 463$ K and $T_{k,1} = 300$ K, respectively. The air mass flow rate was $G_A = 15$ g/s, and for droplets, it was $G_L = 1$ g/s. The swirling number was $S = 0.7$. The initial mean-mass gas velocity was $U_{in} = 35$ m/s, Reynolds number was $Re = U_{in} 2R_1/\nu = 7 \times 10^4$, and mean monodispersed droplets inlet diameter was $d \approx 55$ μm. The results of comparisons are shown in figure 5 in two stations at distances from the flow separation cross-section $x = 26$ mm ($x/H = 0.52$) and 56 mm ($x/H = 1.12$). The longitudinal mean component of the droplets velocity is characterized by the pronounced maximum. The dispersed phase velocity in the axial part of the channel has a negative value that proves the involvement of droplets in the flow separation area.

**Figure 4.** The effect of thermophysical properties on heat transfer enhancement ratio for various droplets mass fraction. Solid lines are water droplets, dashed lines are ethanol droplets. $I - S = 0.25$, $2 - 0.5$.

**Figure 5.** Radial distributions of axial kerosene droplet velocities in two stations from separation cross-section at $x = 26$ and 56 mm. 1 – measurements of [11], 2 – LES results of [12], 3 – author’s simulations.
Conclusion
The 3D mathematical model has been developed for simulation of the swirling turbulent two-phase flow in a sudden pipe expansion in the presence of droplets evaporation. In the two-phase non-swirling flow behind a sudden pipe expansion ($S = 0$) there is a secondary corner vortex, which is absent in the swirling flow. In the swirling flow, two recirculation zones are shown: the first is located in the axial part of the pipe and is formed by flow rotation, and the second one is situated in the near-wall part of the pipe. The flow swirl leads to an increase in the intensity of heat transfer (more than 2 times in comparison with the non-swirling mist flow at other identical inlet conditions). Evaporation of droplets leads to a significant increase in the heat transfer intensity in the swirling two-phase flow (more than 2.5 times in comparison with the single-phase flow with other identical parameters). The ethanol droplets evaporate faster than water droplets and the values of volume fraction of ethanol droplets are lower than those for water droplets. The magnitude of maximal heat transfer enhancement is higher for ethanol droplets than for water droplets. The simulations quite well agree with the measured data for a confined two-phase swirling flow (the difference of the measured and predicted parameters does not exceed 15%).

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