Numerical modeling of flow structure and heat transfer in a mist turbulent flow downstream of a pipe sudden expansion

Maksim Pakhomov^a and Viktor Terekhov

Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Sciences, 630090, Novosibirsk, Russia

Abstract. Turbulent droplet-laden flow downstream of a sudden pipe expansion is numerically studied using Eulerian two-fluid model. The model is used to investigate the effect of droplet evaporation on the particle dispersion and on the gas phase turbulence modification. Turbulence suppression in the case of evaporating droplets is hardly observed near the wall, and the level of turbulence tends to the corresponding value for the single-phase flow regime. In the flow core, where evaporation is insignificant, a decrease in the level of gas turbulence (to 20% as compared to a single-phase flow) can be observed. The maximal effect of droplet evaporation is obtained in the wall region of the tube. A considerable increase in the maximal value of heat transfer on adding the evaporating droplets to the separated flow is shown (more than 2-folds as compared to the single-phase flow at a small value of droplet mass concentration of $M_{L1} \leq 0.05$). The addition of the solid non-evaporating particles causes a slight increase in the maximum value of heat transfer in the case of small particles and a decrease in heat transfer in the case of large particles.

1 Introduction

Two-phase droplet-laden separated flows are observed in many engineering and natural processes, such as cyclonic separation, flame stabilization in internal combustors, pneumatic transport, and many others. The separated flow is a typical two-dimensional shear flow consisting of several zones: main core flow, shear layer, recirculation, and flow relaxation regions. Each zone has specific features and typical length and time scales. The interactions between finely dispersed phase and turbulent gas-phase flows are very complex, and many of these interactions remain poorly understood [1]. Gas-droplet flows are usually inhomogeneous and anisotropic and often include flow separation and heat transfer between two-phase flow and the wall surface. A review of experimental and numerical works revealed that the effect of dispersed phase on the turbulence modification by particles in two-phase separated flows is an extremely complex phenomenon even in the case of gas-particle flows without phase changes.

The aim of the present short communication is to examine the effect of evaporating droplets on gas turbulence modification and heat transfer enhancement in sudden pipe expansion flow. The number of papers that have examined two-phase separated flows with evaporating droplets is very limited [2, 3]. These few studies do not provide sufficient information to evaluate all the factors

^a Corresponding author : pakhomov@ngs.ru

affecting the flow structure, particle dispersion, and turbulence modification in sudden pipe expansion flows with evaporating droplets.

2 The mathematical model and numerical realization

The authors of the present paper used the Eulerian two-fluid approach for the modeling of dispersed phase, which treats the particulate phase as a continuous medium with properties analogous to those of a fluid [3]. This technique involves the solution of a second set of Navier–Stokes-like equations in addition to those of the carrier (gas) phase. A one-point probability density function (PDF) [4, 5] of the particle velocity for describing the action of small particles on turbulence is used. The governing mean and fluctuating equations for both phases are described in detail [3]. Gas–droplet turbulent flow is numerically predicted by the set of steady-state axisymmetrical Reynolds averaged Navier-Stokes (RANS) equations. Gas phase turbulence was modeled with the use of elliptic-blending second-moment closure [6]. Two-way coupling is achieved between dispersed and carrier phases in the mean and fluctuating transport. Particles' mean and fluctuating flow interactions are described by the two-way coupling model [3]. The volume fraction of the dispersed phase is lower $\Phi_1 < 10^{-4}$ and the droplets are fine ($d_1 < 100 \mu\text{m}$); therefore, the effects of inter-particle collisions are neglected when treating the hydrodynamic and heat and mass transfer processes in the two-phase flow [3]. Validation analysis of the developed model for both single-phase and two-phase flows in sudden pipe expansion was performed in [3].

The mean transport equations for both gas and dispersed phases and the second moment closure model are solved using a control volumes method on a staggered grid. The QUICK scheme [7] 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 [8], which couples velocity and pressure.

The first cell is located at a distance $y_+ = yU_*/\nu = 0.3\text{--}0.5$ from the wall, where U_* is the friction velocity obtained for the 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 350×100 control volumes along the axial and radial directions is used. A more refined grid is applied in the recirculation region and in the zones of flow detachment and reattachment.

3 Numerical results and discussion

Numerical modeling is carried out for a monodisperse gas–droplet mixture in the initial cross-section, and then the droplet size is changed due to the evaporation process. The diameter of the pipe is $2R_1 = 20 \text{ mm}$ before expansion and $2R_2 = 60 \text{ mm}$ behind the expansion, the expansion ratio is $\text{ER} = (R_2/R_1)^2 = 9$, and the step height is $H = 20 \text{ mm}$. The mean-mass gas flow velocity before detachment is $U_{m1} = 10\text{--}30 \text{ m/s}$, and the Reynolds number for the gas phase varies within the range $\text{Re}_H = HU_{m1}/\nu = (1.33\text{--}4) \times 10^4$. The initial velocity of the dispersed phase is $U_{L1} = 0.8U_{m1}$. The Stokes number in the mean motion is $\text{Stk} = 0.04\text{--}5$, and the initial mass fraction changes within the range $M_{L1} = 0\text{--}0.1$. Computations are performed at a uniform wall heat flux density $q_w = 1 \text{ kW/m}^2$. The case with the particles of $d_1 = 30 \mu\text{m}$, $\text{Stk} = 0.4$ is the basic one in this study.

All simulations are performed for both the evaporating and non-evaporating cases. In the case of non-evaporating particles, the predictions are carried out without consideration of the phase transition of the dispersed phase and with consideration of the thermal-physical properties of the two-phase flow. This case is artificial, but it allows us to analyze the effect of dispersed phase evaporation on the transfer processes and heat transfer in the separated two-phase flow.

The radial profiles of mass fraction of the dispersed phase are shown in Fig. 1a for the cases of evaporating droplets (continuous lines) and the non-evaporating particles (dashed line). A sharp

decrease in the concentration of particles is observed due to their dispersion over the tube cross-section in the separation region. It should be noted that the low-inertia droplets at low Stokes numbers of $Stk < 1$ ($d_1 < 50 \mu m$) (lines 1 and 2) are entrained well in the separated flow, and are available in almost the entire tube cross-section. The near-wall zone of the pipe ($r/H > 1.2$) is practically free from particles due to intense evaporation. The large droplets with $Stk = 4$ ($d_1 = 100 \mu m$) are not involved in the area of the recirculation flow but are mainly in the shear mixing layer and in the flow core. In the case of non-evaporating particles, their concentration in the wall region of the tube is higher than in the case of the evaporating droplets.

The profiles of the turbulent kinetic energy (TKE) in the two-phase separated flow along the pipe are shown in Fig. 1b, where k_0 is turbulence of the gas phase in the single-phase flow (without particles or droplets). In the two-phase flow, the TKE is suppressed by finely dispersed droplets in comparison with the single-phase one. This effect increases with the size of the dispersed phase, which is consistent with the data of studies on separated flow with solid particles [1, 2, 7]. Small particles ($Stk < 1$) are involved well in the turbulent motion of gas and take some energy away from the carrier medium. The turbulence suppression in the case of evaporating droplets is not observed in the wall zone and $k/k_0 \approx 1$ because this area is free of particles and the level of turbulence tends to the corresponding value for the single-phase flow regime. In the flow core, where evaporation is insignificant, a decrease in gas turbulence is observed (to 20%). It should be noted that the maximal effect of droplet evaporation is noticeable in the wall region of the pipe (the difference is up to 10%). An increase in TKE is observed and $k/k_0 \approx 1$ far from the cross-section of the flow detachment ($x/H = 15$) because most of the droplets have already evaporated.

The effect of the Stokes number (the initial size of droplets) on the magnitude of maximal Nusselt numbers is shown in Fig. 2. The local Nusselt number is calculated by the following relationship: $Nu = q_w H / [\lambda (T_w - T_m)]$, where λ is the coefficient of heat conductivity of the gas flow, and T_w and T_m are the wall temperature and mean-mass temperature of the gas flow, respectively. The increase of the droplets' mass fraction intensifies the heat transfer significantly. This effect cannot be explained by flow turbulization on the addition of the dispersed phase. The main reason of the heat transfer intensification is the using of latent heat of droplets evaporation. This effect increases with an increase in the amount of dispersed phase. Two characteristic areas in the distribution of Nu_{max} in the investigated range of particle sizes should be noted. An increase in the initial droplet diameter has the more complex influence on heat transfer in the two-phase separated flow. Heat transfer enhancement is observed in the range of small particles, and then a drastic decrease occurs at Stokes numbers of $Stk > 0.25$. The dispersed phase is not involved in the separated motion for the largest droplets with diameter $d_1 = 100 \mu m$ and $Stk = 4$. The heat transfer approximately corresponds to the value typical for the single-phase flow in the recirculation zone. The heat transfer rate increases due to the evaporating droplets in the near-wall zone behind the point of flow reattachment. This behavior of the maximal heat transfer is caused by the effect of various factors: more intense evaporation of small droplets, a decrease in the rate of their inertial precipitation, and weaker involvement of large particles in the separated flow. The increase in mass concentration of the dispersed phase causes a significant increase in heat transfer between the two-phase flow and wall as compared to the single-phase flow ($Nu_{max} = 51$). It should be noted the maximal increase in heat transfer in the gas-droplet flow occurs in the region of small particles, which intensively penetrate into the recirculation zone and thus reach the pipe wall.

This work is supported by the Russian Science Foundation (Project No. 14-19-00402).

References

1. J.R. Fessler, J.K. Eaton, J. Fluid Mech. **314** 97 (1999)
2. K. Hishida, T. Nagayasu, M. Maeda, Int. J. Heat Mass Transfer **38** 1773 (1995)
3. M.A. Pakhomov, V.I. Terekhov, Int. J. Heat Mass Transfer **66** 210 (2013)
4. I.V. Derevich, L.I. Zaichik, Fluid Dynamics **23** 722 (1988)
5. M.W. Reeks, Phys. Fluids A **3** 446 (1991)

6. A. Fadai-Ghotbi, R. Manceau, J. Boree, Flow, Turb. Combust. **81** 395 (2008)

7. B.P. Leonard, Computer Meth. Appl. Mech. Eng. **19** 59 (1979)

8. J.P. Van Doormaal, G.D. Raithby, Numerical Heat Transfer, pt. A **7** 147 (1984)

Figure 1. Radial droplets mass fraction distribution (a) and gas phase turbulence modulation (b) along the axial coordinate. 1 – evaporating droplets, 2 – non-evaporating particles. $M_{L1} = 0.05$, $Stk = 0.4$, $d_1 = 30\text{ }\mu\text{m}$.

Figure 2. The effect of Stokes number on the variation of maximum Nusselt number in separated droplet-laden flow. 1 – $M_{L1} = 0.01$, 2 – 0.05, 3 – 0.1.