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Effect of sudden constriction of a flat duct on forced convection in a turbulent droplet-laden mist flow

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Numerical modeling of the flow structure and heat transfer in a gas-droplet turbulent flow in a duct with forward-facing step is carried out. The two-dimensional RANS equations are used in the numerical solution. The Eulerian two-fluid approach is used for describing the flow dynamics and heat transfer in the gaseous and dispersed phases. The turbulence of the carrier phase is described using an elliptical Reynolds stress model with taking the presence of dispersed phase. It is shown that finely-dispersed droplets are involved in the separation recirculation motion of the gas phase. The addition of evaporating droplets to a single-phase turbulent flow in the forward-facing step leads to a significant intensification of heat transfer (more than 2 times) compared to a single-phase air flow, all other parameters being equal. This effect is enhanced with an increase in the initial mass fraction of the water droplets.

Keywords: Numerical simulation, Reynolds stress transport model, forward-facing step, droplet evaporation, turbulence, heat transfer enhancement.

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The issue of cooling of heated elements of structures subjected to thermal loads and the associated problem of heat transfer intensification still remain one of the most topical in current engineering. The use of passive heat transfer intensifiers, which are positioned on surfaces and feature protrusions and (or) dimples of various shapes [1–3], is one of the most efficient ways to enhance the heat transport. The examination of influence of protrusions of various shapes located on the surface of a duct or a pipe on the flow structure and the heat transfer in both forced [1–3] and free [4] convection of a single-phase liquid is important in this context. Another well-known way to raise the heat transfer well above the level corresponding to traditional forced convection in a single-phase medium flow consists in evaporation of droplets of various liquids dispersed in gas flows [5].

Separation of a two-phase flow, the formation of a flow recirculation region, and its subsequent reattachment following a sudden constriction of a flat duct or pipe (forward-facing step) are common in flowing past an airfoil or heat-power equipment elements and in nature (flow past sediments on the bottom of rivers, dunes, etc.; see Fig. 1). This effect is central to the processes of turbulent mixing and heat transport. Such flows have a relatively simple geometry. However, their structure if fairly complex even in the simpler case of flowing past a backward-facing step. The case of flowing past a forward-facing step is more complicated due to the presence of two flow recirculation regions that form after its separation. The boundary layer detaches from the surface on approach to a forward-facing step. The length of this small flow separation region is $x_{R1} = (1-1.5)h$ [6]. Beyond a sudden constriction of a duct, a region of flow separation from its sharp edge forms. The length of this region is normally several times greater than the step height: $x_{R2} = (1.7-4)h$ [6].

Note that very few studies focused on the structure of flow and the heat transfer in a turbulent gas-droplet flow flowing past two-dimensional obstacles (backward-facing steps and obstacles of other shapes) have been published to date [7–10]. It was demonstrated experimentally and numerically in these papers that the heat transfer intensifies considerably (by a factor up to 5) compared to the case of a single-phase flow in a smooth duct at a fixed Reynolds number. We have already performed detailed numerical studies of the structure of flow, turbulence, and the heat transfer in separation gas-droplet flows encountering a sudden constriction of a pipe [7] and a flat backward-facing step [8]. The validity of the numerical code used in this research was verified by comparing the results with measurement data on the structure of flow and the heat transfer for a gas-droplet flow behind a backward-facing step [9].

As far as we know, a gas-droplet flow flowing past a forward-facing step has not been examined yet. In the present study, the influence of a sudden constriction of a flat duct on the local structure of a turbulent flow and the heat transfer in a separation gas-droplet flow with evaporating droplets is examined numerically.

The problem of dynamics of a two-phase gas-droplet turbulent flow with an interphase heat transfer flowing past a flat forward-facing step (Fig. 1) is considered. Two-dimensional steady-state RANS (Reynolds-averaged Navier–Stokes) equations written with account for the influence of particles on transport processes in gas [8] are used to solve this problem. The Eulerian approach is applied to characterize the dynamics of flow and heat

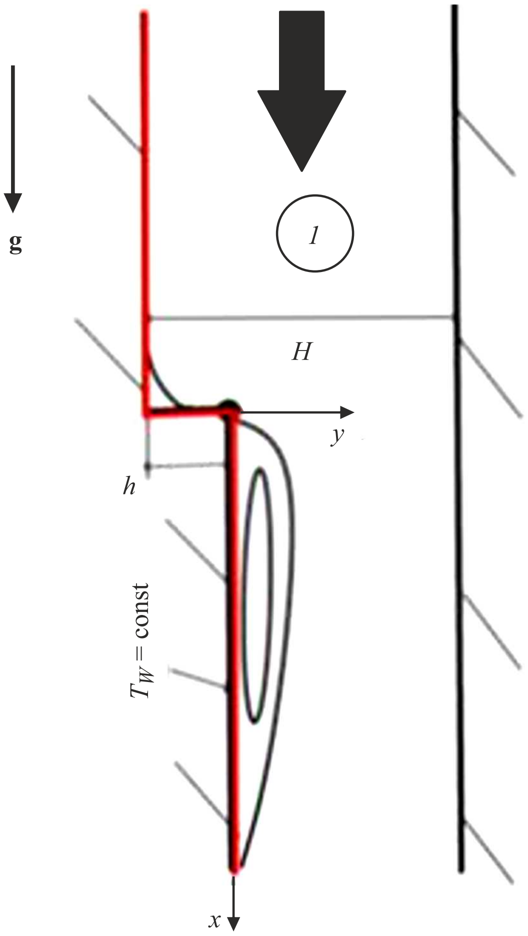

Figure 1. Scheme of a gas-droplet flow flowing past a forward-facing step. *1* — Gas-droplet flow. The wall with a heated surface is highlighted in red (a color version of the figure is provided in the online version of the paper).

and mass transfer in gas and disperse phases. Turbulence of the carrier phase is characterized using an elliptical Reynolds stress transport model [11] written with account for the dispersed phase [12]. The schematic flow diagram is presented in Fig. 1. The volume fraction of droplets is low: $\Phi_1 = M_{L1}\rho/\rho_L < 2 \cdot 10^{-4}$ (M_{L1} is the initial mass fraction of droplets and ρ and ρ_L are the densities of gas and droplets, respectively); in addition, the droplets themselves are rather small (their initial diameter $d_1 = 20\,\mu$m). Therefore, the breakup and coalescence of droplets in a flow are neglected [7,8].

We have already compared calculated data with the results of experiments [13] with a two-phase turbulent flow of gas with solid particles flowing past a backward-facing step without heat transfer. These data were reported in [7,8] and are not presented here. A satisfactory agreement with measurement data [9,13] was obtained (the difference did not exceed 15%). There results were used as a basis for numerical modeling of a gas-droplet flow flowing past a forward-facing step.

All numerical calculations were performed for a monodisperse gas-droplet mixture at the duct inlet and for the case of a downward flow. The channel height upstream of a sudden constriction is $H = 60$ mm, step height $h = 20$ mm, and constriction ratio $\mathrm{ER} = (H - h)/H = 2/3$ (Fig. 1). The origin of coordinates corresponds to the cross section of sudden constriction of a two-phase flow. The mass-averaged velocity of gas upstream of the separation cross section is $U_{m1} = 5$ m/s, and the Reynolds number for the gas phase is $\mathrm{Re} = hU_{m1}/\nu = 6.7 \cdot 10^3$. Water droplets are added to a single-phase air flow in the inlet cross section of the computational domain (i.e., at a distance of $5h$ from the cross section of sudden constriction of a two-phase flow), and their initial velocity $U_{L1} = 0.8U_{m1}$ does not vary over the channel height. The initial mass fraction of water droplets and vapor are $M_{L1} = 0{-}0.1$ and $M_{V1} = 0.005$. The diameter of water droplets in the inlet cross section is $d_1 = 20\,\mu$m. The Stokes number in averaged motion is $\mathrm{Stk} = \tau/\tau_f = 0.06$, where $\tau = \rho_L d_1^2/[18\mu(1 + 0.15\mathrm{Re}_L^{0.687})] = 1.2$ ms is the dynamic relaxation time of particles; $\mathrm{Re}_L = |\mathbf{U}_S - \mathbf{U}_L| d_1/\nu$ is the Reynolds number of the disperse phase based on the interface velocity; $\mathbf{U}_S$ and $\mathbf{U}_L$ are the vectors of actual velocity of the gas phase at the position of a particle [14] and droplets, respectively; and $\tau_f = 5H/U_{m1} = 20$ ms is the characteristic turbulence scale [9,12]. The expression for τ_f is used for the flow after both a sudden constriction of a pipe [7] and a flat backward-facing step [8]. At $\mathrm{Stk} \ll 1$, particles are entrained into separation motion of the gas phase; at $\mathrm{Stk} > 1$, the disperse phase is not involved in recirculation motion [9,12]. The temperature of air and droplets at the inlet is $T_1 = T_{L1} = 293$ K. The temperature of the wall with a step is $T_W = \mathrm{const} = 373$ K, and the opposite smooth wall is thermally insulated. The wall was heated throughout the entire length of the computational domain to prevent the formation of liquid spots on it. The results of preliminary calculations for a single-phase flow in a flat duct with height H and a length of $75H$ were used to set the input distributions of parameters of the gas flow. Thus, a fully hydrodynamically stabilized flow of the carrier phase (air) is present at the inlet cross section of the computational domain.

A numerical solution was obtained using the finite-volume method on a structured grid. The authors Eulerian home code was used to find this solution. The QUICK procedure of the second order of accuracy was applied to convective terms of differential equations. Central differences of the second order of accuracy were used for diffusion flows. The SIMPLEC finite-volume consistent procedure was used to correct the pressure field. All calculations were performed on a „base“ grid containing 400×100 control volumes (CVs). The length of the calculation section upstream of the sudden duct constriction was $5h$, and the section behind the constriction was $10h$ in length. In order to verify that the obtained solution is independent of the number of computation cells, we performed calculations with grids containing 200×50 CVs

(„rough“ grid) and 600×150 CVs („fine“ grid). The difference in calculated data on the turbulent kinetic energy of the carrier phase and the Nusselt number between the „base“ and „fine“ grids was below 0.1%. A further increase in the CV number had no significant effect on the results of numerical calculations. Calculations were performed on a grid with clustering toward all solid surfaces and in flow recirculation regions. At least 10 CVs were used to resolve the mean flow field and turbulent characteristics of a two-phase flow in the viscous sublayer ($y_+ < 10$), and the first computational node was located at distance $y_+ \leq 1$ from any of the walls.

Transverse distributions of the turbulent kinetic energy (TKE) of the carrier phase for a two-phase gas-droplet flow in six cross sections upstream and downstream of a forward-facing step reveal that the TKE value in the mixing layer is the highest (Fig. 2). The gray rectangle denotes the boundaries of a forward-facing step. The TKE for a two-dimensional flow was determined as

$$2k = \langle u_i' u_i' \rangle = u'^2 + v'^2 + w'^2$$
$$\approx u'^2 + v'^2 + 0.5(u'^2 + v'^2) \approx 1.5(u'^2 + v'^2).$$

The turbulent kinetic energy increases on approach to the duct constriction. The maximum turbulence of the gas phase was found in the mixing layer and at $x/h \approx 2$. The turbulence value decreases on approach to the reattachment point. Turbulization of the flow in this cross section is associated with separation flow past a forward-facing step. This holds true for both single-phase and two-phase flows. The TKE distributions for the carrier (thin solid curves) and disperse (dashed curves) phases in a gas-droplet flow are similar in shape to the distribution for a single-phase flow (thick solid curves). Note that the turbulence level of the gas phase gest suppressed when evaporating water droplets are added to the flow (up to 15%) . The turbulent energy of water droplets remains lower than the corresponding value for the gas phase throughout the entire length of the computational domain, but also reaches its maximum at $x/h = 1{-}2$. This is indicative of entrainment of liquid droplets into the gas motion and their interaction with turbulent vortices of the gas phase.

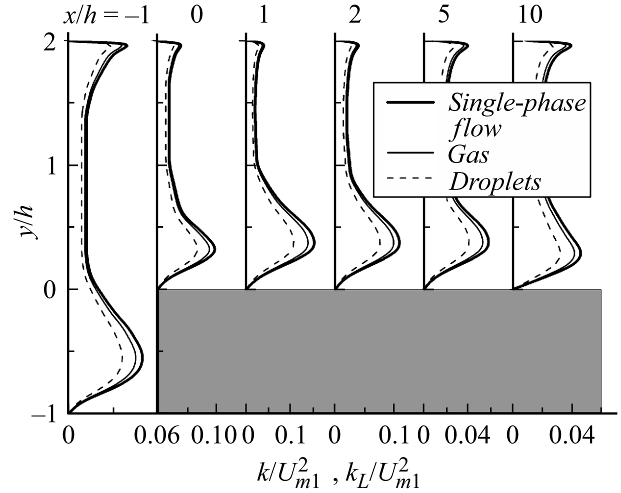

Figure 2. Profiles of distribution of the turbulent kinetic energy for a single-phase flow ($M_{L1} = 0$) (thick solid curves) and the carrier (thin solid curves) and disperse (dashed curves) phases at $M_{L1} = 0.05$ over the longitudinal coordinate after a sudden constriction. $\mathrm{Re}_H = 2 \cdot 10^4$, $\mathrm{Re} = 6.7 \cdot 10^3$, $d_1 = 20\,\mu$m, Stk = 0.06.

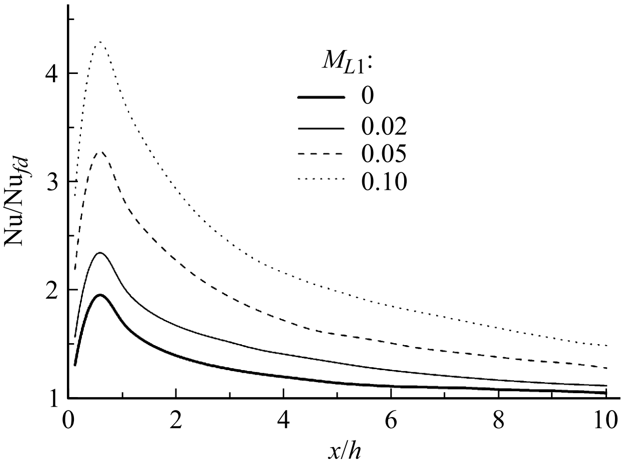

Figure 3. Heat transfer in a separation gas-droplet flow behind a sudden constriction under variation of the initial mass fraction of droplets. $\mathrm{Nu}_{fd} = 36$, $\mathrm{Re}_H = 2 \cdot 10^4$, $\mathrm{Re} = 6.7 \cdot 10^3$, $d_1 = 20\,\mu$m, Stk = 0.06.

The introduction of evaporating droplets into a separation single-phase flow results in significant intensification of heat transfer (a more than 2-fold increase is observed at $M_{L1} = 0.1$) compared to the one in a single-phase flow (Fig. 3) with the same flow conditions. A more than 2-fold enhancement of heat transfer relative to a single-phase separation flow ($M_{L1} = 0$) is also observed. This effect grows stronger with increasing initial concentration of water droplets. A sudden constriction of flow induces a marked enhancement of heat transfer intensification relative to the case of a well-developed air flow in a flat duct under a fixed Reynolds number even for a single-phase flow (Nusselt number $\mathrm{Nu}_{fd} \approx 36$). Compared to the single-phase flow regime, the heat transfer intensifies both in the recirculation region ($x_{R2}/h < 2.75$) and in the region of flow relaxation. This corroborates our conclusion that droplets are entrained into a separation flow. As droplets evaporate and one moves in the downward flow direction, the heat transfer rate tends to the corresponding value for a single-phase stabilized flow in a flat duct beyond a constriction. The maximum of heat transfer for a forward-facing step is localized in the flow recirculation region. Under these conditions, the length of the main separation region is $x_{R2} = 2.75h$, and the length of the small separation region upstream of a step is $x_{R1} = 1.1h$. In the case with a flat backward-facing step, the maximum of heat transfer is roughly aligned with the point of flow reattachment for both single-phase [2] and two-phase [7,8] flows.

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Conflict of interest

The authors declare that they have no conflict of interest.

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