Particle dispersion and turbulence modification in a dilute mist non-isothermal turbulent flow downstream of a sudden pipe expansion

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Abstract. Flow, particles dispersion and heat transfer of dilute gas-droplet turbulent flow downstream of a pipe sudden expansion have been numerically investigated for the conditions of heated dry wall. An Euler two-fluid model with additional turbulence transport equations for gas and particulate phases was employed in the study. Gas phase turbulence was modelled using the elliptic blending Reynolds stress model of Fadai-Ghotbi et al. (2008). Two-way coupling is achieved between the dispersed and carrier phases. The partial equations of Reynolds stresses and temperature fluctuations, and the turbulent heat flux equations in dispersed phase by Zaichik (1999) were applied. Fine droplets get readily entrained with the detached flow, spread throughout the whole pipe cross-section. On the contrary, large particles, due to their inertia, do not appear in the recirculation zone and are presented only in the shear layer region. The presence of fine dispersed droplets in the flow attenuates the gas phase turbulence of up 25%. Heat transfer in the mist flow increased (more than twice in comparison with the single-phase air flow). Intensification of heat transfer is observed both in the recirculation zone and flow development region in the case of fine particles. Large particles enhanced heat transfer only in the reattachment zone. Comparison between simulated results and experimental data of Hishida et al. (1995) for mist turbulent separated flow behind a backward-facing step shows quite good agreement.

1. Introduction
The separated flows downstream of a pipe sudden expansion are frequently encountered in technical applications, e.g. cyclone separators, stabilizing of flame in combustion chambers, dust collectors and many others. The detachment effects the momentum, heat, and mass transfer processes and strongly determines the turbulent flow structure. Knowledge of the turbulent flow and heat transfer in the pipe sudden expansion flows is important from both theoretical and practical points of view. Thus such

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flows have become a subject of many extensive studies. One-phase separated flows downstream of the pipe sudden expansion were reported in many publications (see the references in reviews [1–3]).

Two-phase separated flows behind the pipe sudden expansion or backward-facing step have been found in many technical applications. The effect of solid or liquid particles on transport process in the gas phase becomes more pronounced with increasing size and mass concentration of the particulate phase. Detailed information concerning the turbulent flow, the velocities and temperature distributions of phases, and particles dispersion over the pipe cross-section is an important matter for optimization of evaporation or combustion processes. Two-phase separated flows were investigated by [4–14]. The authors showed that light particles are entrained in the circulating flow, whereas heavy particles escape trapping in the separation zone by traversing the shear flow region. In the wall zone dispersed impurities are accumulated (preferential concentration). It is noted that papers [4–11] were provided for the flows with solid particles without heat transfer between the wall and two-phase flow, and works [12–14] are devoted to investigations of gas-droplets flows with heat transfer.

The PDA measurements and numerical computations of flow characteristics and heat transfer between the flat plate and gas-droplets mist after backward-facing step using the PDA method were performed in [12]. It was showed that there is the large heat transfer enhancement behind the reattachment region. Heat transfer increased by even a little mist adding to the air flow due to the effect of vaporization [13]. It was experimentally found that the mist flow was very useful for heat transfer enhancement especially in the recirculation region.

A Reynolds-averaged Navier-Stokes (RANS) model with modified $k$-$\varepsilon$ low-Reynolds number (LRN) model in the case of water droplets was developed in [14]. The authors used the Euler two-fluid approach [15] for computations of two-phase flows. Initially the model of [15] was developed for the gas-particles flows but the authors of [14] used this model for description of flows with variable droplets size due to evaporation process. The effect of mass concentration of droplets and their size on the structure of separation flow region and heat transfer were analyzed in detail. The results obtained are compared with previous experimental and numerical data for two-phase flows developing downstream of a sudden pipe expansion.

The aim of the present study was numerical examination of the effect of evaporating droplets on particle dispersion, turbulence modification and heat transfer in two-phase mist turbulent flow downstream of a pipe sudden expansion.

2. Problem statement

In the present paper, evolution of dilute gas-droplets turbulent flow in the downstream region of a pipe sudden expansion was numerically examined. The volume concentration of the dispersed phase was assumed to be lower than ($\Phi_1<10^{-4}$), and the particles were assumed to be sufficiently fine ($d_1<100 \, \mu m$), so that, according to [16] the effects of inter-particle collisions could be neglected when treating hydrodynamic and heat and mass transfer processes in the two-phase flow, where $d$ was the droplets initial diameter.

All computations were performed for monodispersed gas-droplets flow at uniform wall heat flux density ($q_w=1 \, kW/m^2$). The computational domain was the pipe with the zone of sudden expansion. The pipe surface was dry, so no liquid film from deposited droplets formed on the wall. This assumption for heated channels was allowably (see [17]). This condition is valid, if the temperature difference between the wall and the droplet is higher than 40 °C. The droplet temperature along its radius remains constant since Biot number is $Bi = \alpha_d/d/\lambda_L<<1$, where $\alpha_d$ is the heat transfer coefficient for evaporating droplet and $\lambda$ is thermal conductivity. The subscript $L$ is the dispersed phase.

2.1. Mean equations for the gas phase

The flow was treated as a steady-state, incompressible and axisymmetrical with ignored mass forces. The mean flow was described with the continuity, two momentum, energy equations and equation of vapor diffusion into binary the gas-vapor mixture. The system of RANS equations for a two-phase is given as
\[
\frac{\rho}{d} \frac{\partial U_i}{\partial x_j} = \frac{6J}{d} \Phi
\]

\[
\frac{\partial (U_i U_j)}{\partial x_i} = -\frac{\partial (P + 2k/3)}{\rho \partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial U_i}{\partial x_j} - <u_i u_j> \right) - \left( U_i - U_{iL} \right) \frac{M_L}{\tau}
\]

\[
\frac{\partial (U_i T)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \nu \frac{\partial T}{\partial x_i} - <u_i t> \right) + D_T \left( \frac{C_{Pr} - C_{Pa}}{C_p} \right) \frac{\partial K_v}{\partial x_i} \frac{\partial T}{\partial x_i} - \frac{6\Phi}{\rho \mu d} \left[ \alpha(T - T_L) + JL \right]
\]

\[
\frac{\partial (U_i K_v)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \nu \frac{\partial K_v}{\partial x_i} - <u_i k_v> \right) + \frac{6\Phi}{d}
\]

(1)

Here, \( \tau = \rho_{\infty} d_i^2/(18\mu W) \) is the particle relaxation time with taking into account the deviation from the Stokes power law.

Value of turbulent Prandtl and Schmidt numbers were equal to \( \text{Pr}_T = \text{Sc}_T = 0.85 \). The turbulent heat and mass fluxes in the gaseous phase were determined according to the Boussinesq hypothesis; they have the form

\[
<u_i t> = -\frac{v_T}{\text{Pr}_T} \frac{\partial T}{\partial x_j}, \quad <u_i k_v> = -\frac{v_T}{\text{Sc}_T} \frac{\partial K_v}{\partial x_j}.
\]

2.2. Turbulence second moment closure (SMC) for the gas phase

In the present study the LRN elliptic blending Reynolds stress model of [18] was employed. The transport equations for \( \left< u_i u_j \right> \) and the kinetic energy dissipation rate \( \varepsilon \) can be written in a general form:

\[
\frac{\partial}{\partial x_j} \left< u_i u_j \right> = P_{ij} + \phi_{ij} - \varepsilon_{ij} + \frac{\partial}{\partial x_j} \left( \nu \delta_{im} + \frac{C_p T_r}{\sigma_k} \left< u_i u_m \right> \right) \frac{\partial}{\partial x_m} \left< u_i u_j \right> - \Lambda_d
\]

(2)

\[
\frac{\partial}{\partial x_i} \varepsilon = \frac{1}{T_r} \left( C_{e1} P_{ij} - C_{e2} \varepsilon \right) + \frac{\partial}{\partial x_i} \left( \nu \delta_{im} + \frac{C_{e3} T_r}{\sigma_{e}} \frac{\partial \varepsilon}{\partial x_m} \right) - \varepsilon_d
\]

(3)

Here \( P_{ij} \) is the stress production term; \( P = 0.5P_{ik} \), \( T_r = \max \left[ k/\varepsilon; C_r \sqrt{\nu/\varepsilon} \right] \) is the turbulent time macro-scale; \( \phi_{ij} \) is the velocity-pressure-gradient correlation, well-known as the pressure term, \( \varepsilon_{ij} = 0.5\varepsilon_{kk} \) is the dissipation rate tensor. The blending model [19] for prediction of the \( \phi_{ij} \) is given as

\[
\phi_{ij} = \left( 1 - \beta^2 \right) \phi^W_{ij} + \beta^2 \phi^H_{ij}
\]

(4)

where \( \beta \) is a blending coefficient which goes from zero at the wall to unity far from the wall, \( \phi^H_{ij} \) is any “homogeneous” part (valid away from the wall) model, \( \phi^W_{ij} \) is “inhomogeneous” part (valid in the wall region) model. The equation (4) is not a differential, elliptic equation, and consequently, in order to preserve the non-local influence of the wall, which yields the progressive transition from the homogeneous form to the near-wall form, authors of [20] proposed to use an elliptic equation for \( \beta \), similar to the elliptic relaxation equations:

\[
\beta = L_\beta \nabla^2 \beta = 1.
\]
Here, \( L_T = 0.161 \max \left( \frac{k^{1/2}}{\epsilon}, \frac{\nu^{3/4}}{\epsilon^{3/2}} \right) \) is the turbulent length macro-scale. The constants of the model were presented in detail in [18].

The last terms of the equations of the system (2) \( A_d \) and \( \varepsilon_d \) are the effect of the particles on the carrier phase turbulence [19]:

\[
A_d = \frac{2\rho_f \Phi}{\rho \tau} (1 - f_u) \langle u_i u_j \rangle - \left( \Omega^{el} / \tau - f_u \right) \rho_f \left[ \langle u_i u_k \rangle (U_j - U_{jL}) + \langle u_j u_k \rangle (U_i - U_{iL}) \right] \frac{\partial \Phi}{\partial x_i},
\]

Here, \( f_u = 1 - \exp \left( - \Omega^{el} / \tau \right) \) is the coefficients of entrainment of particles into large scale eddy velocity fluctuation motion of gas phase and \( \Omega^{el} \) interaction time between the droplet and gas phase large-eddy, analogous as in the work [21]:

\[
\Omega^{el} = \begin{cases} 
T_T, & |\bar{U}_i - \bar{U}_{iL}| \leq L_T \\
L_T / |\bar{U}_i - \bar{U}_{iL}|, & |\bar{U}_i - \bar{U}_{iL}| > L_T
\end{cases}
\]

2.3. Governing equations for the dispersed phase

The system of mean equations for the transport process in dispersed phase has the form [14]. The model for the transport of Reynolds stresses \( \langle u_{ij} u_{ik} \rangle \) and temperature \( \langle \theta^e_i \rangle \) fluctuations, and also the turbulent heat flux \( \langle \theta^e_i u_{ij} \rangle \) in dispersed phase were written using the model of [14]. The heat and mass transfer model for a single droplet was described in detail in [22].

3. Boundary conditions, numerical procedures and testing of the model

The numerical solution was obtained using the finite volume method. To convective terms in differential equations, the QUICK procedure was applied. The diffusion fluxes were written using central differences. The pressure field was corrected by the finite-volume SIMPLEC procedure. A computational grid was non-uniform both in the axial and radial direction. Refining the grid was applied in the recirculation zone, in the flow detachment region, and in the reattachment zone. All 2D computations were performed on the grid with 450\( \times \)100 control volumes (CVs). In the case of 3D geometry the grid with 450\( \times \)100\( \times \)16 CVs was employed. Initial conditions at the pipe inlet were used in the form of uniform profiles of all parameters. In the outflow face of the computational domain the condition of parameters derivations in the longitudinal direction equality to zero were set. At the pipe axis, for both phases the conditions of symmetry were adopted. At the wall we used wall impermeability and no-slip conditions for gas. For the dispersed phase the conditions of [22] were adopted. After depositions onto the pipe surface, the droplets were assumed to be momentarily evaporated. At the first stage, the comparison with experimental data for single-phase turbulent pipe sudden expansion flows was performed. The numerical simulations were validated against the experimental data for mean velocities and their fluctuations in [23] and heat transfer in [24].

4. Numerical results and discussion

All computations were carried out for the monodispersed gas-droplet mixture in the initial cross-section. The diameter of pipe before expansion was \( 2R_1 = 20 \) mm, behind expansion it was \( 2R_2 = 60 \) mm, the expansion ratio was \( ER = (R_2 / R_1)^2 = 9 \), and the step height was \( H = 20 \) mm. The gas flow velocity before detachment was \( U_{m1} = 15 \) m/s, Reynolds number for the gas phase was \( Re_{\mu} = HU_{m1}/\nu = 2 \times 10^4 \). The initial velocity of the dispersed phase varied within \( U_{i1} = 0.8U_{m1} \). The initial droplet sized was \( d_L = 0-100 \) \( \mu \)m, and their initial mass fraction changed within \( M_{i1} = 0-0.05 \). The length of numerical domain after the pipe expansion was \( 30H \). The density of heat flux fed to the tube surface
was \( q_w = 1 \text{ kW/m}^2 \). The present numerical study is focused on four droplets diameters (see Table 1). The Kolmogorov length and time scales were calculated with the use of formulas by [11]:

\[
\eta_K = 2R_i \Re_{c1}^{-3/4}, \quad \tau_K = \frac{\eta_K^2}{\nu},
\]

where \( \Re_{c1} = \frac{2R_i < u_{c1} >}{\nu} \) is the Reynolds number and \( < u_{c1} > \) is the root-mean-square (r.m.s.) gas pulsations in the axis of inlet cross-section, respectively.

The change in particles size and their material properties in a wide range can be described by a single dimensionless parameter. It is also used to quantify the level of dispersed phase responsivity to the gas motion. This dimensionless parameter is the Stokes number \( \text{Stk} = \frac{\tau_p}{\tau_f} \), and it is the ratio of particles relaxation time \( \tau_p \) to the appropriate time scale of the carrier phase \( \tau_f \). Here \( \tau_f = 5H/U_1 \) is the large-eddy passing frequency [5, 8]. The dispersed phase with small Stokes number \( \text{Stk} \ll 1 \) is found be in velocity equilibrium with the gas phase. Particles are good responsive to gas phase fluctuations and will move unaffected through eddies. The particles with large Stokes number \( \text{Stk} \gg 1 \) are found be no longer in equilibrium with the fluid phase. They are unresponsive to gas phase fluctuations and will move unaffected through gas eddies.

### Table 1. Description of simulated cases for \( M_{L1} = 0.05 \).

| \( d_1 \) (µm) | \( \eta_K \) (µm) | \( \tau \) (ms) | \( \tau_K \) (ms) | \( \text{Stk} \) | \( \text{Stk}_K \) |
|-----------------|-----------------|----------------|-----------------|----------------|--------------------|
| 0               | 120             | –              | 1               | –              | –                  |
| 10              | 114             | 0.3            | 0.9             | 0.04           | 0.33               |
| 30              | 106             | 3              | 0.75            | 0.4            | 4                  |
| 50              | 100             | 8.5            | 0.67            | 1.2            | 12.7               |
| 100             | 92              | 33             | 0.56            | 4.7            | 58.9               |

In the Figure 1 is shown the schematic representation of the pipe sudden expansion geometry and the predicted streamlines of the gas phase in the mist flow. The flow had a substantial change after the expansion with appearance of the recirculation zone. From Figure 1 it is seen that a secondary vortex exists in the corner region. Firstly the presence of the corner eddy was observed for single phase air flow downstream of the pipe sudden expansion in [24]. It is noted that the single-phase flow displayed the same features qualitatively.
The effect of droplets on gas phase turbulence is studied examining the ratio of turbulent kinetic energy (TKE) for two-phase flow $k$ to that of the single-phase flow $k_0$ at the recirculation zone at $x/H = 6$. It is shown in Figure 2 that the increase of initial diameter of dispersed phase leads to the attenuation of gas phase turbulence. The main effect of turbulence modification (TM) is observed in the shear layer region where $k/k_0 = 0.8$ for $d_i = 100 \, \mu m$. In this area the influence of evaporation on turbulence is very small. In the recirculation zone the value of TKE for the mist flow is roughly coincided with that of the single-phase flow due to droplets evaporation in the vicinity of the wall surface. Almost all sizes of droplets used in this study are within $d_i = 10–50 \, \mu m$ due to dispersion scatter over the pipe radius in the recirculation region. The largest droplets ($d_i = 100 \, \mu m$) practically do not enter into the recirculation zone due to their inertia.

The radial profiles of the dispersed phase mass loading ratio at $x/H = 6$ are shown in Figure 3 for various initial particle diameters. It should be noted that fine dispersed droplets (curves 1 and 2) are found in the separated zone and are scattered in the flow throughout the whole pipe cross-section. For fine droplets their slightly accumulation in the separated area near the wall is observed. On the other hand for larger particles, due to their inertia, it is typical unresponsive into the recirculation bubble and present only in the shear layer (curves 3 and 4). In the wall zone due to evaporation the mass fraction of droplets is much lower than in the axial area of the pipe.

**Figure 2.** Gas phase turbulence modification in the two-phase mist flow across the radial coordinate downstream of the pipe sudden expansion at $x/H = 6$. $H = 20 \, mm$. $Re_H = 2 \times 10^4$, $ER = 9$, $U_1 = 15 \, m/s$. (a): $M_{L1} = 0.05 \, %$. 1 – $d_i = 10 \, \mu m$, 2 – 30, 3 – 50, 4 – 100. (b): $d_i = 30 \, \mu m$, 1 – $M_{L1} = 0.01$, 2 – 0.05, 3 – 0.1.

**Figure 3.** Profiles of droplets mass loading ratio. $M_{L1} = 0.05$, $Re_H = 2 \times 10^4$, $x/H = 6$. 1 – $d_i = 10 \, \mu m$, 2 – 30, 3 – 50, 4 – 100.

One of the crucial parameters of separated flows is the length of reattachment region. The results predicted with the use of the SMC are compared with our previous numerical simulations [14].
Table 2). When the mass fraction was varied the initial size of droplets was constant $d_1 = 50 \mu m$. In the case when of droplet inlet diameter was constant the liquid mass concentration $M_{L1} = 0.05$. For the single-phase flow the mean reattachment point is situated at $x_R/H = 10.6$ from the sudden expansion section. In the case of two-phase flow the reattachment zone is extended. This conclusion disagrees with the measurements previously reported by [7], which found that the reattachment zone in the case of two-phase flow is shorter than in the one-phase flow, becoming more extended in the downstream direction with increasing concentration of solid particles. Note also that, in our computations, with increasing droplet mass fraction the length of recirculation region also became more extended, what complies qualitatively with the data reported in [11, 12, 14].

Heat transfer in the mist separated flow increased (more than by 75 % in comparison with the single-phase air flow). Intensification of heat transfer is observed both in the recirculation region and flow development region in the case of fine dispersed particles. The latter conclusion lends support to the conclusion that finely dispersed particles are entrained with the detached flow. Large particles ($Stk > 1$) added to the flow almost never enter the recirculation zone, the heat transfer intensity in this zone remains roughly unchanged, and enhanced heat transfer is only observed in the reattachment zone. An increase in the initial droplet diameter decreases the Nusselt number due to inter-phase contact area reduction at fixed mass concentration of droplets.

| Droplets mass fraction $M_{L1}$ | Present results | [14] | Droplets initial size, $\mu m$ | Present results | [14] |
|-------------------------------|----------------|-----|-------------------------------|----------------|-----|
| 0                             | 10.2           | 10.6| 0                             | 10.2           | 10.6|
| 0.01                          | 10.2           | 10.6| 10                            | 10.2           | 10.75|
| 0.02                          | 10.25          | 10.8| 30                            | 10.3           | 10.8 |
| 0.05                          | 10.35          | 10.9| 50                            | 10.35          | 10.9 |
| 0.07                          | 10.4           | 11  | 100                           | 10.5           | 10.95|
| 0.1                           | 10.6           | 11.1|                               |                |      |

**Figure 4.** Heat transfer distributions in gas-droplets flow downstream of the pipe sudden expansion along the axial direction. $d_1 = 30 \mu m$, $Re_H = 2 \times 10^4$, 1 – $M_{L1} = 0$, 2 – 0.01, 3 – 0.05, 4 – 0.1.

5. Comparison with experimental results
In the section, the code is compared with measurements by [12] for mean axial velocity and their pulsations of gas and dispersed phases for turbulent gas-droplets flow behind of the single side backward-facing step. We can not find in literature the experimental data for gas-droplets flow downstream of a pipe sudden expansion.

The experimental set up consisted of a flow with the expansion ratio $ER = (h_2/h_1) = 1.14$ and 1.29, where $h_1 = 70 \text{ mm}$ is the channel height before step and $h_2 = H + h_1$ is the channel height after step, the
step height was $H = 10$ and 20 mm, the Reynolds numbers of $Re_H = 5.3 \times 10^3$ and $1.1 \times 10^4$. The free stream velocity just upstream of the separation section was $U_1 = 10$ m/s. The initial mean size of water droplets was $d_1 = 60 \ \mu m$ with initial mass loading ratio $ML_1 = 4.1 \%$. The wall was isothermally heated with $T_W = 308–373$ K. In measurements was realized a dry heated wall condition. The flow direction was downward.

The computational and experimental results streamwise mean velocity profiles of both phases at different locations downstream from the step at $x/H = 1.25, 4, 5$ and $7$ are presented for $H = 20$ mm in Figure 5. Points are the measurements by [12], curves are our simulations. It is seen that it was a recirculation region, where no droplets were observed. The droplets velocity due to their inertia was larger than that of air both in the separated and reattached areas. Due to inertia, droplets do not enter the recirculation flow region and move only in the shear layer. The mean-flow Stokes number for the case of a 20-mm step is $Stk = \tau_f/\tau = 1.1$.

In Figure 6 the two-component turbulent kinetic energy of carrier $(<u'^2> + <v'^2>)/(2U_1^2)$ and dispersed $(<u'^2_d> + <v'^2_d>)/(2U_1^2)$ phases were shown. The same features are observed for both phases. The TKE of droplets was smaller than the gas phase pulsations across the transversal coordinate. The maximum level of dispersed phase fluctuations was located in separated shear layer and increased in the downstream direction as for the gas phase. This result showed that droplets are dispersed in the transversal coordinate by interaction with large eddies of the carrier phase in the shear layer. This is characteristic both for experiments [12] and for our computations.

The effect of step height on the heat transfer rate is illustrated in Figure 8 for two steps of 10 mm and 20 mm. Here, $St_{0, max}$ is the maximum Stanton number for the one-phase air flow, and $x_R$ is the flow mean reattachment length. The Stanton number was calculated by formula $St = \alpha/(\rho C_P U_1)$ where $\alpha$ is the heat transfer coefficient. The analysis of data in Figure 7 shows that heat transfer in the case of gas-droplet flow increases appreciably (more than 50 %) for both step heights. Predicted heat transfer for step $H = 20$ mm (Stk = 1.1) is larger than that for $H = 10$ mm (Stk = 2.2) at the reattachment point. For $H = 10$ mm value $St/St_{0, max}$ is higher in the area of reattached flow than in the case of the step with 20 mm high. In the recirculation region heat transfer for $H = 20$ mm is higher than that for $H = 10$ mm because at lesser Stokes number droplets are better entrained and dispersed through the recirculation region.
flow. The maximum locus of heat transfer is far behind the reattachment point \((x - x_p)/x_p = 2 - 4 \) for \(H = 10\) mm, what can be explained by lower entrainment of particles into the detached flow at large Stokes numbers. Maximum heat transfer for \(H = 20\) mm approximately coincides with the reattachment point.

The results of comparative analysis with experimental results for gas-particles pipe sudden expansion flows and for gas-droplets flow behind the backward-facing step are presented. The numerical data revealed good agreement with measurements of [11, 12] and qualitatively concordance with our previous RANS–\(k-\varepsilon\) model [14].

The results of a comparative analysis with experimental results for gas-particles pipe sudden expansion flows and for gas-droplets flow a past backward-facing step are presented. The numerical data revealed good agreement with the measurements of [11, 12] and qualitatively concordance with our previous RANS-\(k-\varepsilon\) model by [14].

**Figure 6.** Velocity fluctuations of gas (solid lines) and droplets and droplets (dashed lines)
Points are measurements of [12]: open symbols are the gas, closed are dispersed phase; lines are the computations of the present paper. \(H = 20\) mm, \(Re_H = 1.1 \times 10^4\), \(ER = 1.29\).

**Figure 7.** Heat transfer enhancement in gas-droplets flow behind the backward-facing flow. Symbols are experimental results by [12], curves are computations of the present paper. \(T_w = 338\) K, \(1 - H = 10\) mm, \(Re_H = 5.3 \times 10^3\), \(ER = 1.14\); \(2 - H = 20\) mm, \(Re_H = 1.1 \times 10^4\), \(ER = 1.29\).

**Conclusions**
The separated gas-droplet flow downstream of the pipe sudden expansion has been investigated with the Euler two-fluid model. The gas phase turbulence was modeled with the use of SMC with taking into account the presence of evaporating droplets. Two-way coupling is achieved between dispersed
and carrier phases. The partial Reynolds stresses and temperature fluctuations, and turbulent heat flux equations in dispersed phase were utilized.

Fine dispersed droplets (with small Stokes number) get readily entrained with the detached flow and scattered over the whole pipe cross-section. On the contrary, larger particles (with large Stokes number), due to their inertia, did not get into the recirculation region and move throughout the shear layer region. In the wall zone, due to droplet evaporation, mass concentration of liquid droplets is much lower than in the axial region of the pipe.

In the case of two-phase flow the length of reattachment zone is extended with the increase of droplets mass fraction and their initial diameter. Gas phase turbulence in the two-phase flow depends strongly on droplet mass concentration and their inlet size. The increase of these parameters lead to attenuation of gas phase turbulent kinetic energy. The maximal value of gas turbulence energy can be observed in the shear layer.

Heat transfer in the mist separated flow increased (more than by 75% in comparison with the single-phase air flow). Intensification of heat transfer is observed both in the recirculation region and flow development region in the case of fine dispersed particles. Large particles (Stk > 1) added to the flow almost never enter the recirculation zone, the heat transfer intensity in this zone remains roughly unchanged, and enhanced heat transfer is only observed in the reattachment zone.

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