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Influence of Issued Jet Conditions on Mixing of Confined Flows

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The development of the velocity and scalar fields in a coaxial jet mixer has been experimentally investigated applying simultaneously Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) methods. Mixing of a turbulent jet (water solution of Rhodamin 6G) issued from a long round nozzle (*l/d* = 60) with co-flow (water) was studied. Because of the nozzle length the boundary layers of the inner flow already merged upstream of the jet exit. The issued jet conditions were changed installing vortex generators (tabs) at the nozzle exit. The tabs of rectangular and triangular forms with heights of 13 - 15 % the inner nozzle diameter accelerated mixing significantly but the scalar field developed to the homogeneous state faster than the velocity one. Turbulent characteristics measured downstream of the jet exit gave evidence the mixing specific behind the rectangular and triangular tabs.

1. Introduction

Mixing enhancement of gas and fluid flows is interesting for different technical applications from turbo-jet engines to mixers in the chemical industry. Among of different mixer constructions a jet coaxial mixer is a quite simple and rather effective device. Mixing proceeds due to the velocity gradient at the boundary of the co-flow and the jet issued from the centrally positioned nozzle: the high speed flow entrains the slower one. This entrainment generates the shear or mixing layers which development downstream determines the mixing intensity. So, the variation of the mixing layer development causes the variation in mixing.

The application of vortex generators (tabs) at the nozzle exit intensifies mixing stronger than any other known methods as has been noted by Samimy et al. (1993). The effect of tabs installed in smooth contraction nozzles, when laminar or turbulent boundary layers were formed at the jet exit, was observed if their heights were larger than the thickness of the boundary layer (Bradbury and Khadem, 1975, Samimy et al., 1993, Zaman et al., 1994 and Reeder and Samimy, 1996). These studies supplied information for various tab configurations and flow conditions and also have shown that a tab produced a pair of counter-rotating streamwise stationary vortices which enlarged the entrainment and distorted the cross section of the original round jet. The extent and the form of this deformation depend on the number of tabs. The sources for the generation of streamwise vorticity have been identified by Bohl and Foss (1996) and by Zaman (1999). The dominant source comes from the pressure hill formed upstream of the tab because the flow braking. The second source, again owing to the pressure gradients on the tab's surface, is the vortex shed from the sides of the tab.

The most part of known studies of the tabs effect considered their influence examining only the transformation of the velocity field. Mixing was estimated by the mean velocity decay at the flow axis (Bradbury and Khadem, 1975) or calculating the entrainment - the "mass flux" (Zaman et al.,1994, Zaman, 1999). These quantities were used as the primary measure for the comparative study and details of mixing were hided. Simultaneously measurements of the velocity and scalar fields not only improve the mixing understanding but also result in the cross correlation distributions of velocity and scalar fluctuations. These correlations describe the turbulent fluxes $\overline{u'c'}$ and $\overline{v'c'}$ which distributions are usually used to validate the models approximations in numerical calculations.

The present study aims to simultaneously measure the velocity and scalar fields in a coaxial jet mixer applying PIV and PLIF methods. The above mentioned investigations of tabs effect did not show the difference in the effectiveness of the triangular and rectangular vortex generators because the direct comparative examinations of these tabs were not carried out. At the same time the delta tabs – triangular tabs which were tilted downstream about 135°, have shown the superiority. It seems that detailed examinations of the velocity and scalar fields just behind the nozzle with different tabs elicit the influence specific of the tabs form.

2. Experimental Set Up and Running Conditions of Experiments

The measurements have been carried out in the closed water channel described in the paper by Zhdanov and Hassel (2012). The test section of the channel consists of the mixer and the equipment (Figure 1a).

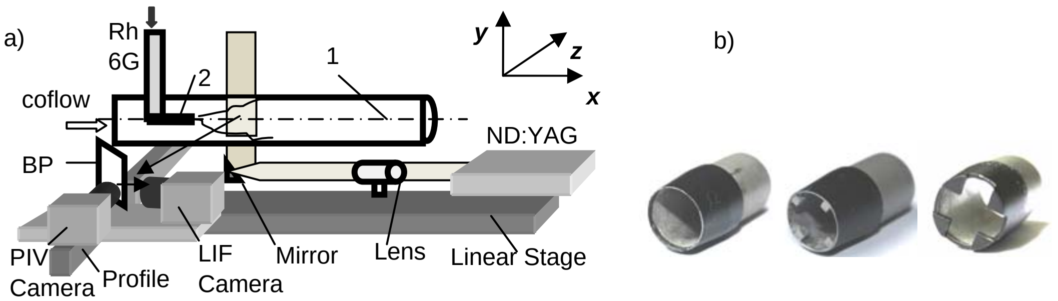

Figure 1: Scheme of the test section (a); the mouthpieces (b) applied in the experiments, from left to right D0, D1, and D2

The mixer was formed by two co-axial tubes: glass tube 1 with an inner diameter of D = 0.05 m and steel tube 2 with an inner diameter of d = 0.01 m (nozzle), which was co-axially positioned. The horizontal length of the nozzle was equal 60d, so the developed flow was formed upstream of the nozzle exit. To reduce the distortion of the flow image due to the curvature of the glass tube the mixer was placed into the glass rectangular box filled with water.

The velocity and scalar fields were measured by identical CCD cameras (14 - bit PCO 1600, with a resolution of 1600x1200 pixels and the frame rate of 30 fps at full resolution). The cameras were placed on a common assembly plate and they observed the same flow image using a beam splitter plate (BP). The assembly plate was fixed to the profile fastened on a linear stage. This stage also carried a laser Nd: YAG, lenses and a mirror which were used to produce a laser sheet. Both cameras were equipped with Nikkor 50 mm lens and separating rings PK-11A that resulted in the image magnification of 0.173. The host computer synchronized the cameras and the laser.

Mixing of the jet (water solution of Rhodamin 6G) and co-flow (water) have been carried out at the coflow-to-jet flow rate ratio equal to 5. The exit jet velocity was turbulent (Reynolds number $Re_d = 10^4$) and higher than the co-flow one.

The exit jet conditions were varied applying three mouthpieces with the same inner diameter (d = 0.01 m) but different exit cross sections because of the tabs (Figure 1b). The mouthpiece without generators was used as the reference one (D0). Two other were manufactured with tabs of different form and sizes: the square tabs ($h = 1.5\cdot 10^{-3}$ m, D1) and the triangular tabs with the angle at the apex of 90° (the high of $h = 1.3\cdot10^{-3}$ m, the base of $2.6\cdot10^{-3}$ m, D2). Their exit cross sections were reduced by 11 % (D1) and 8 % (D2) in comparison with the cross section of the reference mouthpiece (D0).

The laser sheet of $0.7\cdot10^{3}$ m thickness crossed the mixer in the vertical plane along the centre line (z = 0). The light reflected from the particles in the flow and exited the dye molecules, which started to radiate the longer wavelength light. The light reflected off the particles was collected by the camera with the laser-line band pass interference filter 532 nm (Edmund Optics). The radiated light of the dye molecules passing through the broad pass filter BP600 nm with 50 nm FWHM (Edmund Optics) entered to another camera.

Preliminary studies of different but uniform dye concentrations were executed. The Gaussian nature of the laser beam, which results in the variations of the dye intensity over the laser sheet, was taken into account by the each pixel calibration. A linear response of the radiated light intensity was observed within the interval 0 - 0.2 mg/L at the laser pulse energy of 21 mJ.

3. Results

The distributions of the velocity, concentration and their fluctuations are presented in the dimensionless art. The values of the velocity and the concentration at the nozzle exit (U_i, C_i) and at the flow axis (U_0 and C_0) in measured cross sections were used for the normalization. The measurements were done at the different distances from the nozzle exit which were determined by numbers of the mixer diameter (D).
The axial velocity and the concentration started to decay at the flow axis earlier (0.3 < x/D < 0.6) as a result of the enlarged entrainment of the co-flow into the jet due to the tab effect (Figure 2).

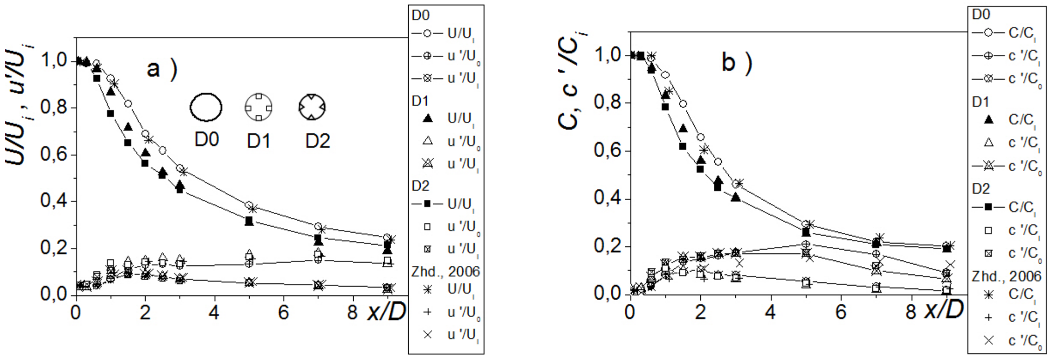

Figure 2: Decay of the axial velocity and the concentration along the mixer axis

This decay was stronger behind the mouthpiece D2 within the interval 0.3 < x/D < 2.0 but downstream the development for both mouthpieces differed insignificantly. The data for the reference mouthpiece correlated well with the ones presented in the study by Zhdanov et al. (2006).
The measurements were done for two positions of the mouthpieces D1 and D2. At first the mouthpiece was installed in the nozzle so that the vertical laser sheet coincided with two opposite tabs ((the plane of 0°). In this plane the pairs of counter-rotating vortices generated by the tabs pumped the secondary flow to the jet axis and the jet diameter was reduced (left part of Figure 3a-e). The second line measurements were done when the mouthpieces were rotated by 45°. At this position vortices of the same sense from different pairs ejected the jet fluid and the velocity and concentration profiles expanded (right part of Figure 3a-e). The difference between the axial velocity profiles measured at two planes (0° and 45°) degraded to the distance x/D=2 and the profiles behind the mouthpieces D1 and D2 became fast the same but wider than the reference one. The velocity gradient decreased across the mixer owing the tabs but it was still observed at the distance x/D = 9 (Figure 9f).

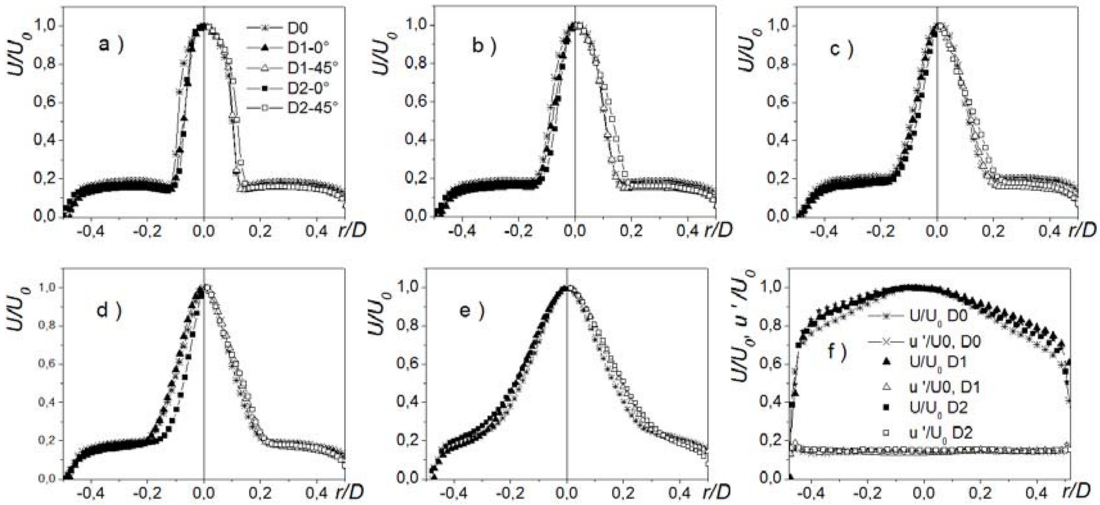

Figure 3: Distributions of the axial velocity: a) x/D = 0.06; b) 0.3; c) 0.6; d) 1.0; e) 2.0, f) 9.0

The radial velocity V showed a positive offset which increased downstream (Figure 4). This velocity in the plane of 0° responsible for the entrainment of the co-flow fluid and it increased in the case of the mouthpieces with tabs. Noticeably smaller value of this velocity behind D1 seems because of the closer location of the counter-rotating streamweise vortices that complicates the entrainment. The velocity decreased in the plane of 0° to the distance x/D = 0.6 but from x/D = 1 it increased again changing its behaviour. The velocity distributions became already similar in both planes and were practically identical from x/D=2 up to x/D = 9 (Figure 4a, b, c). This development of the radial velocity was quite similar the velocity development behind the reference mouthpiece.

The radial velocity just behind the mouthpiece D2 was higher and varied a little within the interval 0 < x/D ≤ 1.0 that obviously resulted in the larger entrainment. The velocity monotonically decreased downstream in both planes (0° and 45°) and the profiles differed insignificantly at the distance x/D = 3, i.e., the influence of the streamwise vortices was already neglected. The gradient of V almost decayed to the distance x/D = 9.0 and the uniform velocity distribution was observed across the mixer.

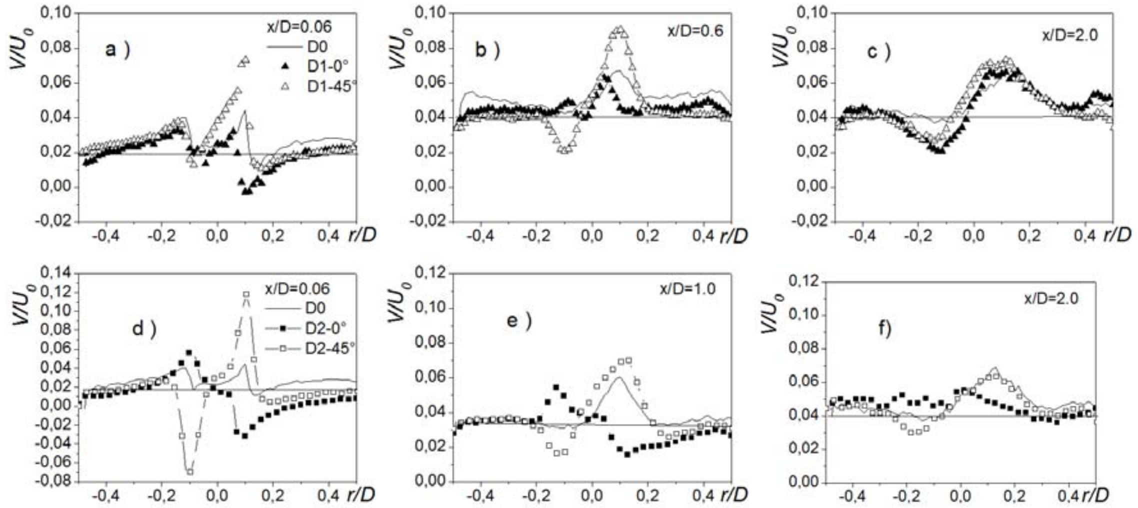

Figure 4: Distributions of the radial velocity behind the mouthpieces D1 (a - c) and D2 (d - f)

The difference between the concentration profiles in the planes of 0° and 45° disappeared at x/D = 2.0 for both mouthpieces D1 and D2 (Figure 5a-e). The jet issued from the mouthpiece D2 expanded stronger because of the larger initial entrainment (the profiles were wider than the ones behind D1) up to x/D = 2. The distinctions in the profiles behind the mouthpieces D1 and D2 became insignificant within the interval 3 ≤ x/D < 5 but downstream the profiles behind the mouthpiece D1 expanded already stronger. So, the streamwise vortices generated by rectangular tabs influenced the jet for longer distance. Nevertheless in both cases the uniform concentration distributions were across the mixer at x/D = 9 (Figure 5f).

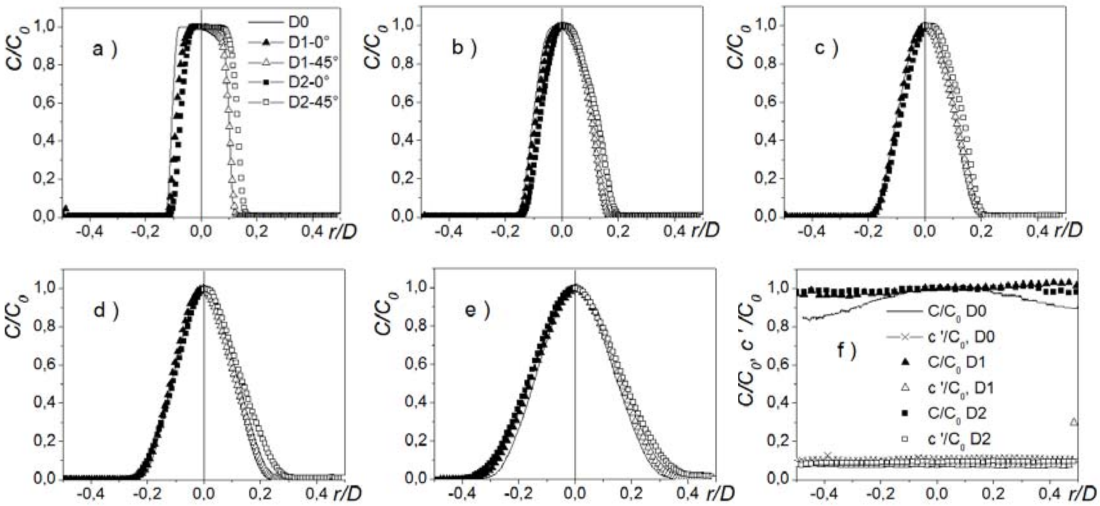

Figure 5: Concentration distributions: a) x/D = 0.06; b) 0.3; c) 0.6; d) 1.0; e) 2.0; f) 9.0

The interaction of the jet with streamwise vortices caused the velocity fluctuations in the mixing layers to grow just near the jet exit. They decreased a little downstream (x/D=0.3) but then increased again up to the distance x/D = 2.0 (Figure 6). The fluctuations (r.m.s) were higher and they expanded stronger behind the mouthpiece D2 but only in the interval 0 < x/D < 1.5, downstream they became smaller. The fluctuation profiles in two planes were practically the same downstream x/D = 3 for the mouthpieces D1 and D2. The absolute values of fluctuations monotonically decreased within the interval 1 < x/D < 9 but due to the decrease in the mean velocity the normalized fluctuations increased again about 18% at x/D = 5.0 and 7.0 (Figure 2a).

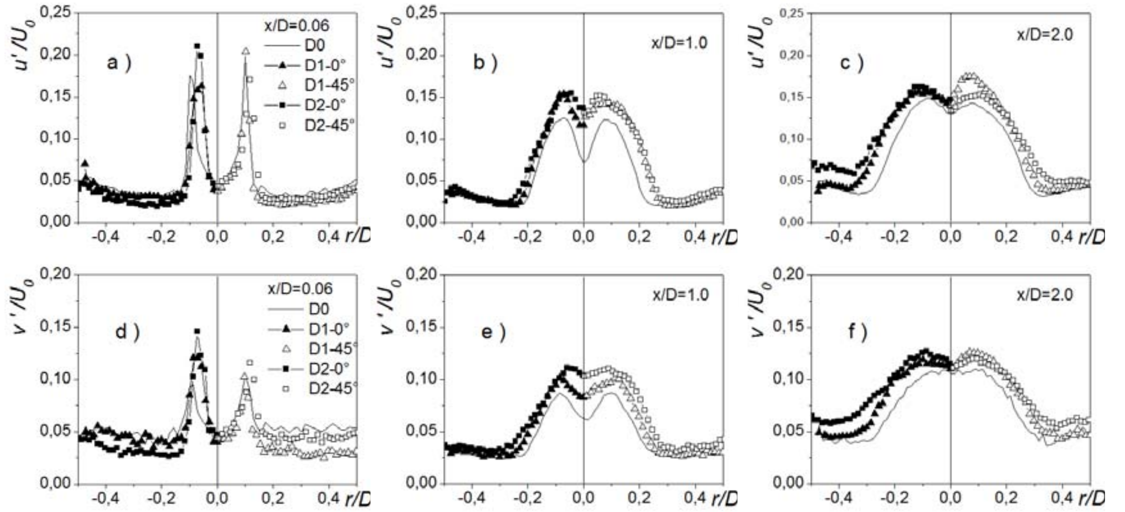

Figure 6: Distributions of the axial (a-c) and the radial (d-f) velocities fluctuations

The enlarged entrainment by the induced vortices resulted in higher scalar fluctuations in the mixing layers which also expanded stronger than the ones behind the reference mouthpiece D0 within the interval 0 < x/D < 3.0. Due to the fact the scalar fluctuations (r.m.s.) increased at the flow axis earlier and they were higher behind the mouthpiece D2 up to the distance x/D = 3.0 where the fluctuations for all mouthpieces hardly differed at the flow axis (Figure 7a-e). The fluctuations in all cases developed to the uniform distribution across the mixer but behind the mouthpieces D1 and D2 they started to decay earlier (x/D ≥ 3) than behind the reference one as a result of the decrease in the concentration gradient (Figures 5f and 7f).

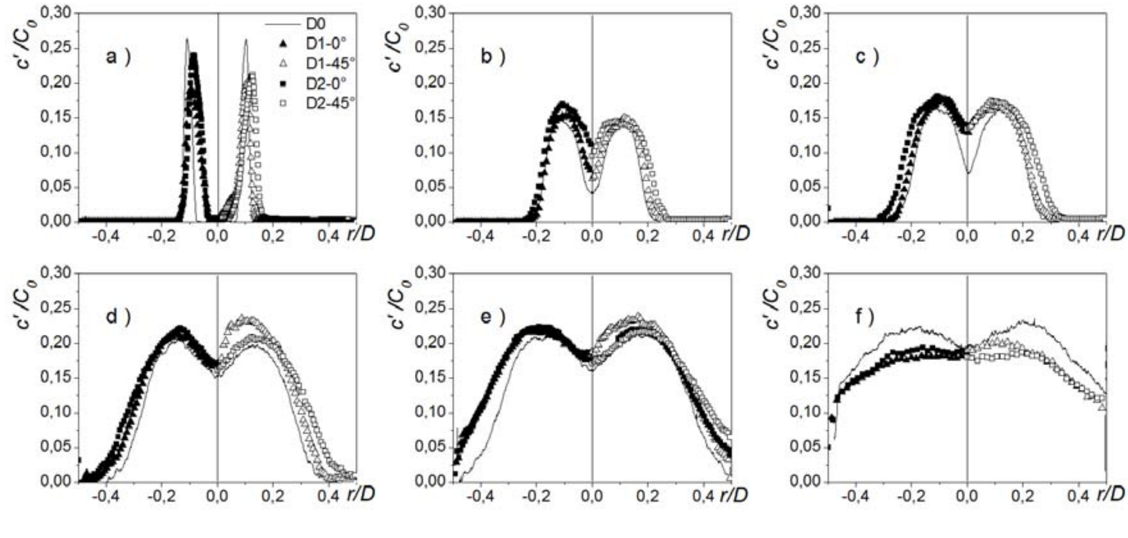

Figure 7: Distributions of the concentration fluctuations: a) x/D = 0.06; b) 0.6, c) 1.0; d) 2.0; e) 3.0; f) 5.0

The turbulent fluxes ($\overline{u'c'}$) increased because of the tabs but they differed insignificantly near the jet exit. A little higher values behind D2 were observed only up to the distance x/D = 1.0 where the distinctions already disappeared and downstream (1< x/D < 3) the fluxes became stronger behind the mouthpiece D1 (Figure 8a-c).

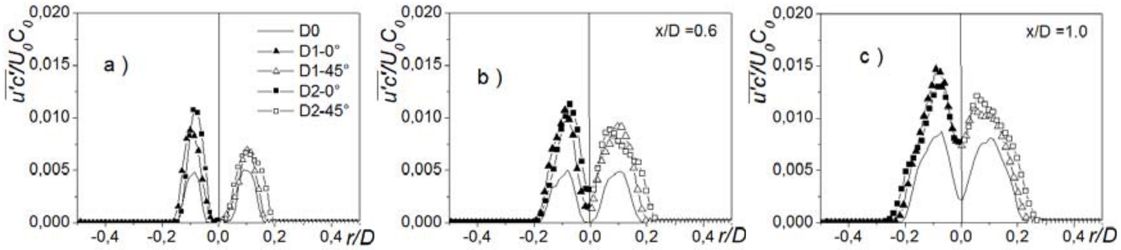

Figure 8: Development of the turbulent fluxes: a) x/D = 0.3; b) 0.6; c) 1.0

The fluxes were practically identical in all cases at the distance x/D = 5 and started to decay behind the mouthpieces D1 and D2 downstream x/D=5 but behind the reference mouthpiece later (x/D ≥ 7).

4. Conclusions

The investigations have shown that mixing of the developed turbulent jet with the co-flow can be significantly enhanced by rather small (0.13 ≤ *h/d* ≤ 0.15) vortex generators (tabs). The enlarged entrainment of the co-flow fluid to the jet within the interval 0 < x/D <1 accelerated the velocity and scalar development but the last one reached the quasi-homogeneous state noticeably earlier.
The investigation has shown that the triangle tabs in spite of the smaller blockage effect resulted in larger entrainment just behind the jet exit. The streamweis vortices generated by these tabs affect mixing for shorter distance than the vortices generated by rectangular tabs.
Two factors determine the distinction in the effect of the rectangular and triangular tabs: a) size and b) form. It seems that the larger counter-rotating vortices generated by the rectangular tabs (D1) started to interact with one another at ones and complicated the entrainment to the jet near the nozzle exit in the plane of 0°. But the influence of these large vortices on the flow development was observed far downstream and due to the fact the final mixture uniformity (x/D = 9) was practical the same as behind the mouthpiece D2.
Vortices shed from the edges of the tabs. The edges are located at 90° in the case of triangular tabs and they are parallel one to another in the case of the rectangular tabs. The advantage of triangular tabs seems due to the larger distance between the centres of the counter-rotating streamweis vortices of every pair that resulted in favourable conditions for the entrainment near the jet exit (the higher radial velocity in the plane of 0°). It seems that these vortices developed at some angle to the jet flow and because of the increasing distance between them their influence on the transport processes disappeared downstream.

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