Fachtagung "Lasermethoden in der Strömungsmesstechnik"
6. – 8. September 2005, BTU Cottbus

INFLUENCE OF THE MIXER GEOMETRY ON THE SCALAR FIELD FORMATION

V. Zhdanov, N. Kornev, E. Hassel
Fachbereich Maschinenbau und Schifftechnik, Lehrstuhl für Technische Thermodynamik, Universität Rostock, 18059 Rostock, A.Einstein Str.2

Abstract

Experimental investigation of the mixing of two mediums, water and aqueous rhadomin solution 6G, has been carried out at the axis-symmetrical jet mixer with different nozzle diameters. The influence of the ration *D/d* on the development of the velocity and scalar field at the mixing regime with recirculation zone is analyzed. The velocity field has been controlled by one component LDA and the scalar distributions across the mixers have been measured with LIF method. The Reynolds number based on the nozzle parameters was Re_d=10000. Autocorrelation functions, integral scale in different cross-section of the mixer have been calculated using the measured scalar distributions. The study showed that the macro-mixing is accomplished earlier when the ration *D/d* is higher but the values of the scalar fluctuations in the quasi-homogeneous mixing state are smaller when the ratio *D/d* is smaller.

Introduction

Jet axis-symmetrical mixers are being widely used in the chemical and food industries for a long time. These relatively simple facilities representing two different-diameter co-axial tubes provide a wide range of possibilities to mix liquid and gas media. The velocity field formation is crucially affected by the flowrate ratio of mixed media and the inner diameter ratio of tubes. As for a wide spectrum of possible flowrate ratios the present study is concerned only with those, at which turbulent ejection of a medium from a nozzle is realized at a velocity that is higher than a co-flow one. Under these conditions the mixing regimes are held to two fundamentally different cases. The first case is the mixing regime when a recirculation zone is formed immediately behind a nozzle. The second is the mixing regime that is looked like a free jet injection. The conditions for generation of the mixing regime are determined from the flowrate-to-diameter ratio, see Henzler H.J., 1978: 1) $D/d > 1 + \dot{V}_D / \dot{V}_d$ 2) $D/d < 1 + \dot{V}_D / \dot{V}_d$;

The velocity field in the mixing regime with a recirculation zone is detailed by Barchilon, Curtet 1964 where it has been found that when the value of the flowrate ratio increases the start of this zone and its center move from the nozzle but its decay boundary remains invariable and is located at the distance *x/D* ~3. This mixing regime is the example of the structure-complex flow with a high level of fluctuations (about 40%) in the recirculation zone. Obviously, this provides a faster scalar leveling over the mixer cross-section. Average velocity fields have been measured using a Pitot tube and velocity fluctuations – by a hot-wire anemometer. The recirculation zone structure is represented as steady-state and symmetric when the obtained values are averaged for a minute, although the instantaneous photos with an exposure time of 1/20 s demonstrate the jet deviation from its symmetry in the case of interaction with the recirculation zone. In the flow region near the jet vortices are generated, and their size and position essentially vary with time. Modern optical methods for diagnostics of dynamic and scalar characteristics of flow enable one to get more exact information on the mixing dynamics of this regime. Interest to this mixing regime is determined by the fact that as our preliminary studies (see Zhdanov 2004) have revealed, the scalar leveling over the mixer cross-section occurs at the distances almost twice as shorter in comparison with the "free jet"-type mixing regime. At the same time those studies have found the formation of essentially asymmetric flow in the recirculation zone. As the design of the channel measuring part had some disadvantages that could provide flow asymmetry, it was cardinally remade. The mixing for two different-diameter nozzles was investigated.

Experimental Set up

Experiments were made in a closed water channel (see Zhdanov 2004). A design of a different-geometry mixer comprised a large constant-diameter plexiglass tube 1 (D_{in} = 50 mm) and nozzle 2 with different inner diameters d_{in} = 3 and 10 mm (Fig.1). The mixer design was modified with the use of detachable sections 3 having the identical length of 430 mm but with different nozzle 2. Mounting section 3 provided tubes 1 and 4 to be coaxial not worse than ±0.3mm. The position of water box 5 remained invariable when blocks 3 were replaced. The co-axiality of nozzle 2 along tube 4 was performed with an accuracy of ±0.3 mm. The length of the horizontal section of the nozzles was equal to 550 mm, and the protrusion of nozzle 2 relative to the plane of the outlet cross-section of tube 4 was 120 mm. Nozzle 2 was fixed in position in tube 4 that was connected with the flanges of block 3 through ring sealing gaskets. Because of this, the angular position of the nozzle relative to tube 1 could be varied by rotating tube 4. The side and lower walls of box 5 were made of plexiglass, and this permitted optical diagnostics of flow in the mixer. Water filling of box 5 diminished the optical distortion due to the curvature of tube 1.

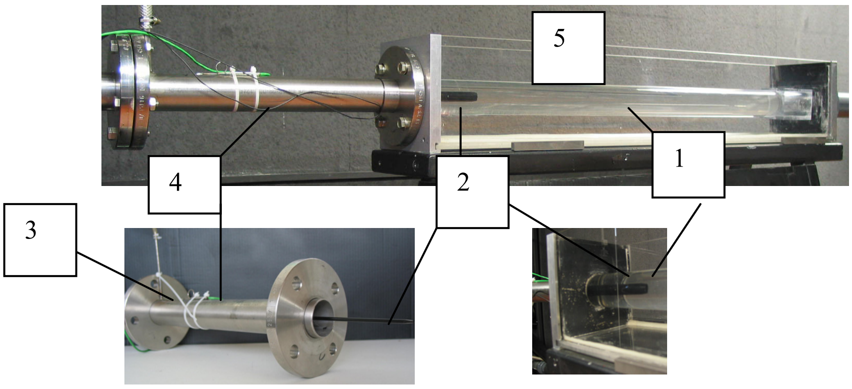

Fig. 1: Test section of the water channel: 1 – outer tube of the mixer; 2 – nozzle; 3 – detachable block with the nozzle; 4 – outer tube of block 3; 5 – water box

The velocity field was measured using a one-component LDA Dantec (Flow Light 1). Average velocity profiles and velocity fluctuations were registered over the mixer cross-sections at a distance of 1 mm from the mixer outlet cross-section up to 9 mixer diameters downstream at three angular positions (0°, 90° and 180°) of the nozzle. The first angular position (0°) of the nozzle is represented by that shown in Fig. 1.

The concentration field was measured by the LIF method. The aqueous rhadomin solution 6G with a concentration of 0.03 mg/1 flowing through the nozzle was served as fluorescing substance. The measuring system comprised a ND: YAG laser operating at 532 nm with 7 ns pulses, a CCD camera (PI-MAX, Roper. Sci. Corp.), optical lenses to form a laser sheet (see Zhdanov 2004).The laser sheet was formed in the vertical plane coincident with the axis of the mixer and flow. The CCD camera was operating in the ROI regime: the radiation intensity of a mixture across the diameter *D* was being measured in the plane of the laser sheet along the linear of 1 pixel wide. The use of an extension ring (Nikon PK-11A) with 50 mm Nikorr lenses enabled one to increase a spatial resolution to 0.3 mm. The data sampling rate depended only on the triggering rate, i.e., on the laser frequency (10 Hz). A file of instantaneous 1000 frames (data acquisition time was equal to 100 s) was being recorded for each mixer cross-section. The 3-fold increase of this interval did not influence the values of the averaged scalar and its fluctuations and resulted in 5% deviations in PDFs. The CCD camera position relative to the laser sheet was fixed and kept for every measured mixer cross-sections. As for velocities, radiation intensities were measured over the same cross-sections.

The jet-fluid mixture fraction was determined by measuring the intensity of laser-induced fluorescence from dye-containing fluid. The intensity normalization to the maximum intensity on the jet axis in the first measured cross-section (*x/D* = 0.1 for the 10 mm dia nozzle and x/*D* = 0.06 for the 3 mm in dia nozzle) was made.

Results

Studies of the development of velocity and scalar (mixture fraction) fields were carried out at the flowrate ratios that provided the mixing regime with a recirculation zone (Q=$\dot{V}_D / \dot{V}_d$ =1.3 and 6.4, 10 for the ratios *D/d* = 5.0 and 13.67, respectively). In all the cases the flow ejection from the nozzle was turbulent at the Reynolds number equal to 10000.

The velocity and scalar fields measured at three angular coordinates of block 3 pointed to the flow asymmetry in the mixer (Fig. 2). The possible reason for this asymmetry was the residual deformation of nozzle 2 after it had been bent through 90 deg. As the length of nozzle 2 from a place of its fixing in tube 4 to the outlet cross-section was 150 mm, this deformation caused the center of the outlet cross-section of the nozzle to move by a distance of 1 mm relative to the mixer axis in the vertical plane.

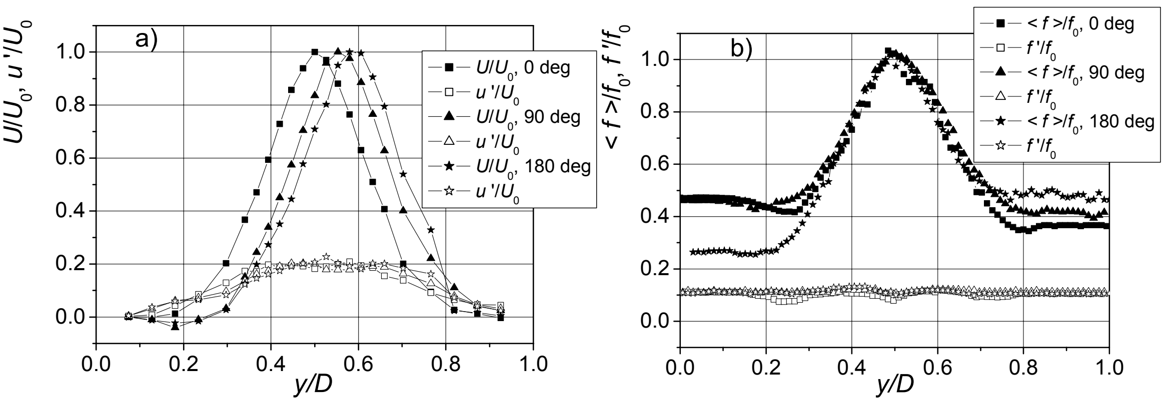

Fig.2: Velocity profiles, mixture fraction and their normalized fluctuations over the cross-section at *x/D* = 1.6 in the mixer with *D/d* = 5

As the flow distortion in different planes was different, the comparative analysis of the development of dynamic and scalar parameters was made in a plane with the minimum flow distortion. Since the velocity and scalar were measured in the mutually orthogonal planes, the velocity distributions in the plane (0 deg) and their corresponding scalar ones in the plane (90 deg) (Fig. 3, 4) were compared.

Due to the mixer walls curvature, the flow velocity field near the walls (about ~4 mm, 0.93 < *y/D* < 0.07) could not be measured and the negative velocity was hardly detected in the mean velocity profiles in the mixers with geometry *D/d* = 5.0 and 16.7. So, from the measured velocity profiles it was difficult to firmly outline the boundaries of the recirculation zone. Barchilon, Curtet 1964, for the same mixing regime but at Q =1.02 and *D/d* =13.4 registered the backflow near the walls within the interval 0.73 ≤ *y/D* ≤ 0.27 and showed that the recirculation zone ended independent of the Q value at *x/D* = 3.0.

In moving away from the nozzle the level of turbulent fluctuations increases, which can be reasonably expected if the development of the recirculation zone is taken into account. The growth of the level of turbulent fluctuations over the range 0.6 < *x/D* < 3.1 qualitatively agrees with the data of Barchilon, Curtet 1964. However, in the present study the maximum level of fluctuations does not exceed 30% as against 80% in the cited reference. It should be noted that up to the cross-sections at *x/D* < 1.6 the difference in the maximum fluctuations of both investigations lies within 25% and it seems is a result of hot-wire measurements. Yet in the present study the maximum normalized fluctuations are determined not in the recirculation zone but over the cross-section downstream of it at *x/D* = 5.1 (Fig.3b, 4b). Downstream the fluctuations decrease and become essentially more uniform over the cross-section.

The presence of the passive scalar and rms values of mixture fractions near the walls at *x/D* = 0.6 indicates the reverse flow (Fig. 3 c). The profiles of mixture fraction expand faster than the corresponding profiles of the mean velocity. Due to the fact, the macromixing is attained over the mixer *D/d* = 5.0 at the distance *x/D* = 5.1, i.e. much prior to the formation of the uniform velocity distribution (*x/D* > 9.1). It is clear that the leveling of the mixture fraction is a result of the recirculation zone effect. This zone from the statistic point of view is a 3-*D* structure that occupies the space between the mixer walls and the jet. The centre of this structure is placed within the interval 2.1 < *x/D* < 2.6 where a noticeable reduction of the rms fluctuations of mixture faction in the flow region adjoined with the jet is fixed (Fig. 3c). The space near the wall that this structure occupies is also maximal in this interval: it spreads, along the mixer radius up to *r/D* = 0.3. Downstream, it seems, the recirculation zone reduces but it still exists behind the section *x/D* = 3.1, i.e. it decays later than it has been noted by Barchilon, Curtet 1964.

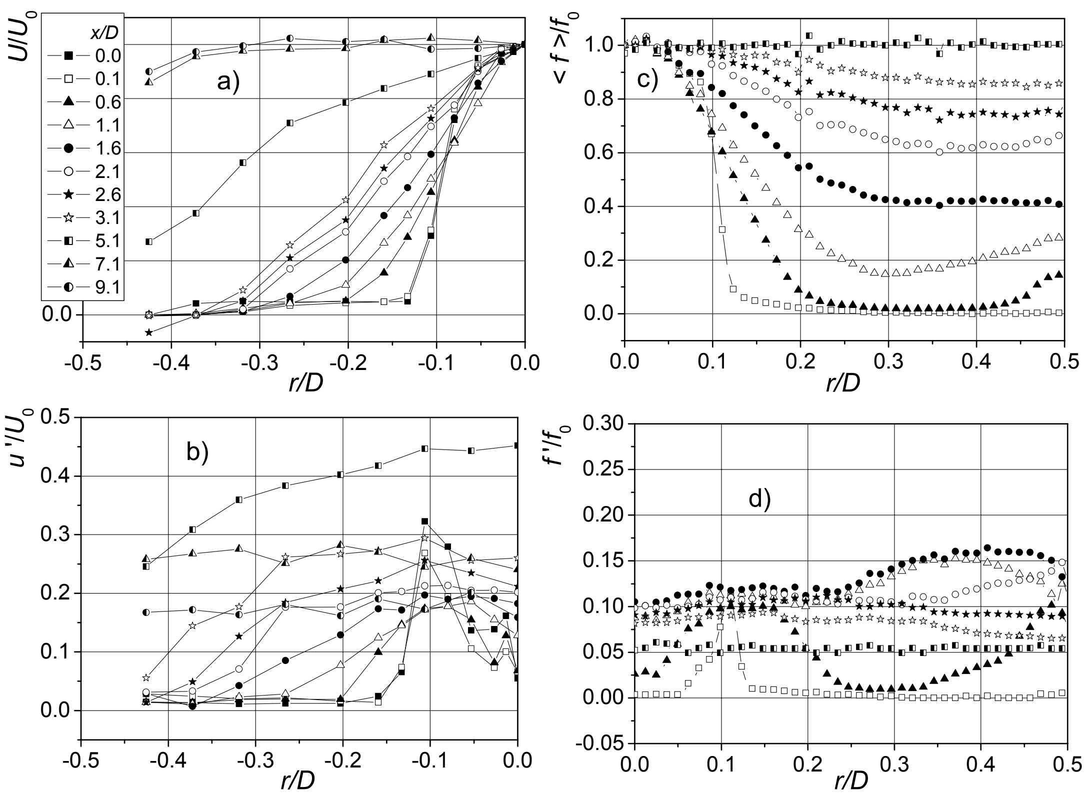

Fig. 3: Profiles of the longitudinal component of the average velocity (a), the mixture fraction (c) and their fluctuations (b, d) in the mixer with *D/d* = 5.0 at Q = 1.3

In the mixer *D/d* =16.7 the developing of the mean velocity profiles in the interval 0.6 < *x/D* < 3.1 is almost the same as in the mixer with *D/d* = 5.0. But some of the features, such as the coordinate, along which the velocity changes its sign (*r/D* = -0.35, *x/D* =1.6), the higher level of turbulence across the mixer indicate that the larger recalculation zone develops (Fig. 4a, b).

The distributions of the passive scalar show that the backflow near the wall is also fixed at the distance *x/D* = 0.6. Due to the weak interaction of the jet and the recirculation zone the scalar expanding is quite slower within the interval 0.6 < *x/D* ≤ 1.1. Downstream the mixing is accelerated so that near quasi-homogeneous distribution across the mixer is formed at the distance *x/D* = 2.6 and at the distance *x/D* = 3.1 the macromixing ends. On the basis of the development of the mixture fraction and rms distributions, one can state that the recirculation zone centre is placed between 1.6 < *x/D* < 2.1 and this zone expands from the wall up to the coordinate *r/D* = ±0.2 in the cross-section that passed its centre. So, it can be emphasized that these sizes of the recirculation zone are in a fair correlation with the ones presented by Barchilon, Curtet 1964, taking account on the difference in the mixer geometry and in the flowrate ratio. Another conclusion from the investigations is that the ratio *D/d* influences the length of the recirculation zone: the lower the ratio the farer downstream from the nozzle this range expands.

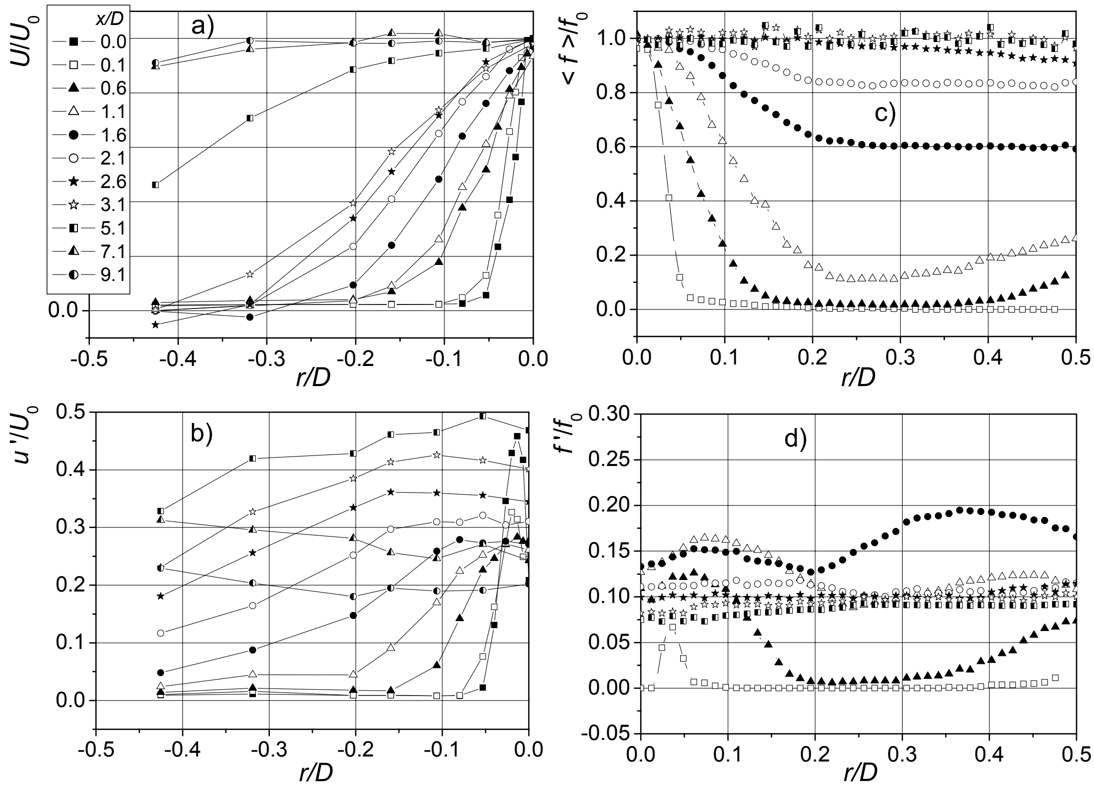

Fig. 4: Profiles of the longitudinal component of the average velocity (a), the mixture fraction (c) and their fluctuations (b, d) in the mixer with *D/d* = 16.7 at Q = 6.4

The high level of turbulent fluctuations of a jet ejecting from the nozzle of 3 mm dia responsible for the mean velocity reduction on the axis just behind the nozzle is consistent with the data Ginevskii, Pochkina 1967 (Fig. 5a). In the mixer with *D/d* = 5.0 where the level of the initial fluctuations on the axis is twice as lower, the flow with a constant velocity is observed up to *x/D* = 0.6. The decay of the average velocity and the passive scalar along the mixer axis much enhances with the increase in the ratio *D/d*. It is peculiar that the growth of the flowrate ratio up to Q = 10, when the mixing regime with the recirculation zone is preserved, practically does not affect the decay of the average velocity while the level of turbulent fluctuations decreases. Irrespective of the mixer geometry, the maximum of turbulent fluctuations is seen over the cross-section at *x/D* = 5.1, i.e. beyond the recirculation zone, and is determined by the low values of the velocity, because the absolute values of fluctuations monotonically decrease downstream, starting with the distance *x/D* = 1.6.

The decay of the passive scalar is in the main determined through that of the average velocity. The passive scalar fluctuations also attain the maximum on the mixer axis over the cross-section at *x/D* = 1.6 (Fig. 5b). Increasing the ratio Q, when the mixer geometry is preserved, not much affecting the decay of the dynamic parameters causes the scalar decay to accelerate and scalar fluctuations to grow.

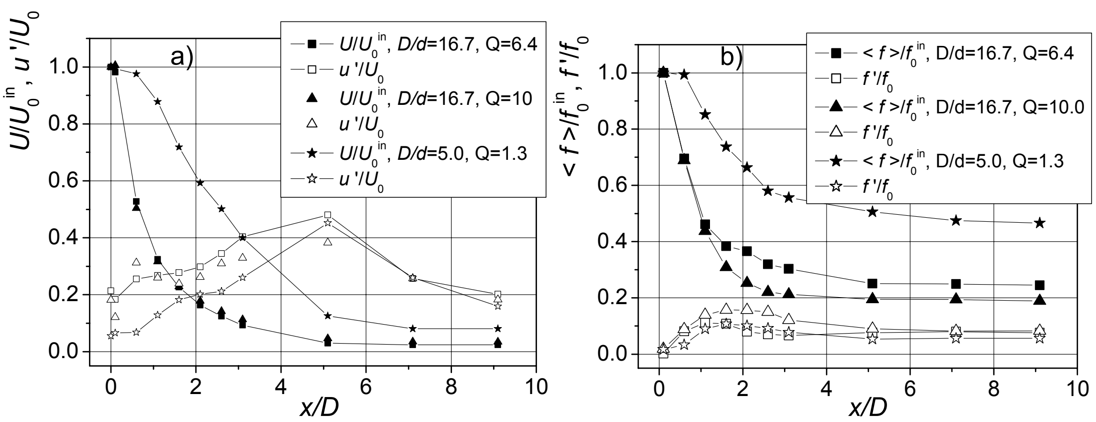

Fig.5: Decay of velocity and scalar fields in the different-geometry mixer

The distinctive features of flow development downstream of different-inner diameter nozzles are more vividly seen in the distributions of the autocorrelation functions obtained using the distributions of the passive scalar *f*(*y*):

$$R_f(y,\eta) = \frac{\overline{f'(y)f'(y+\eta)}}{\sqrt{\overline{f'^2(y)}}\sqrt{\overline{f'^2(y+\eta)}}}$$

The autocorrelation functions are built at different distances from the nozzle for three coordinates over the mixer cross-section (Fig. 6). Thus, the possibility appears to follow the flow history at each of the considered points. The autocorrelation function for the homogeneous flow region is characterized by a single narrow peak of unit size and just this is seen at each flow point over the initial cross-section at *x/D* = 0.1 for mixers with *D/d* = 5.0 and 16.7. Such a distribution is evident of a small scale of interaction between the points adjacent to the considered coordinate. The flow pattern essentially changes already over the cross-section at *x/D* = 0.6.

The strong correlation domain is formed near the both walls for the mixer *D/d* = 5.0 and only from one side in the mixer *D/d* =16.7 (Fig. 6 a,d). For each coordinate *y/D* = 0.13 and 0.87 the correlations decrease up to zero in the jet direction, but again enhance, change their sign by the negative one near the opposite wall (Fig. 6 b,e). The negative correlation between the points placed near the opposite mixer walls evidences that the pulsations in these points are opposite in phase. These points belong to the same recirculation zone and their negative correlation reflects the fact that two parts of the one zone move in counter phase. This fact has been supported by our flow visualizations and it is in the compliance with the observations of the instantaneous flow structure by Barchilon, Curtet 1964.

On the jet axis the autocorrelation function radically does not change, reflecting a quite uniform domain of the scalar distribution. In moving away from the nozzle the area under the peak on the jet axis increases because of the growth of the scale of the point correlations due to jet expansion. It is worth to outline that the coordinate on the jet axis does not correlate with the domains of the recirculation zone. Thus, this zone forming around the jet does not interact with the jet core. The recirculation zone represents a cocoon inside which the jet develops. Maximum expansion of this zone occurs in the mixers at *x/D* = 1.6 and it decays downstream. The influence of the jet diameter or the ratio *D/d* on the dynamics of the recirculation zone development is evident of the fact that for the smaller *D/d* this zone decays earlier. So, for *D/d* = 16.7 at the distance *x/D* = 3.1 the flow over the mixer cross-section is determined by small scales as at the mixer inlet (Fig. 6 f).

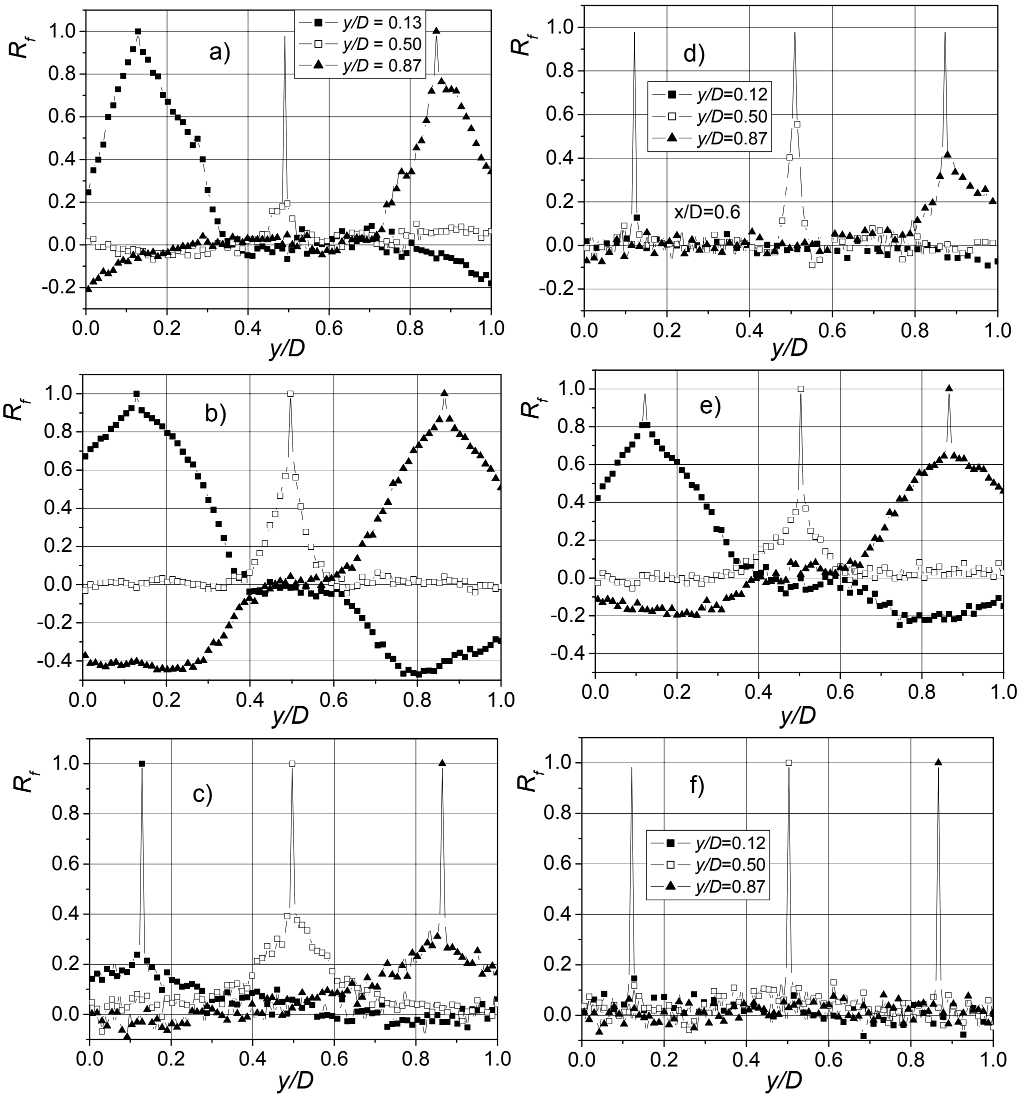

Fig.6: Autocorrelation function distributions across the mixer with *D/d* = 5.0 (a-c) and 16.7 (d-f) at a different distance from the nozzle: a, d) *x/D* = 0.6; b, e) *x/D* = 1.6; c, f) *x/D* = 3.1

The integral scale over the mixer cross-section is calculated using the autocorrelation function R_f:

$$L_f(r) = \int_{-\infty}^{\infty} R_f(r,\eta)d\eta$$

This calculation is rigorously valid for the quasi-uniform state and when essentially different scales are present in the analyzed range, the obtained information on the integral scale evolution is qualitative in nature. The integral scale distributions are normalized to the corresponding nozzle diameter (Fig. 7). Over the initial cross-section of the mixers (*x/D* = 0.1) the integral scales are small and their distribution is rather uniform. The higher values of L_f/d over the jet cross-section ejected from the small nozzle are governed by the fact that the test jet section is at a larger distance from the nozzle measured in nozzle diameters.

In moving away from the nozzle the integral scale quickly increases in the wall region, achieving its maximum values over the cross-sections at *x/D* = 0.6 and *x/D* = 1.1 in the mixers with *D/d* = 5.0 and 16.7, respectively. The maximum values of L_f in the both mixers are practically the same. The scale decays downstream slower in the mixer with *D/d* = 5.0 and for the quasi-uniform state of a mixture ($x/D \geq 5.0$) the scale almost 3-fold larger the corresponding one in the mixer with *D/d* =16.7.

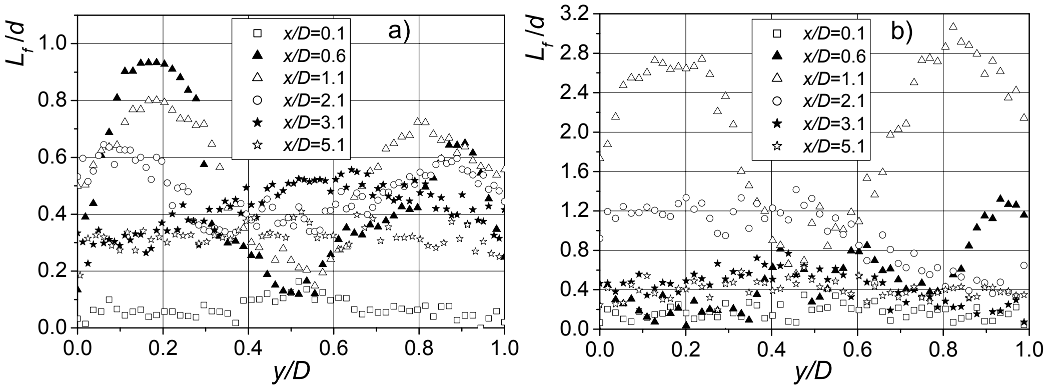

Fig. 7: Integral length variations in the different mixer cross-sections: a) *D/d* = 5.0; b) *D/d* = 16.7

Conclusions

The investigation shows that the geometry of the axis-symmetrical jet mixer, particular the ratio of its diameters *D/d*, influences the development of the mixing through the transformation of the recirculation zone. The macromixing ends in this zone independent of the mixer geometry. But the length of the recirculation zone is the shorter, the bigger the ratio *D/d*. At the same time the longer the recirculation zone, the slower the decay of the integral scale downstream and the smaller the rms mixture fraction fluctuations behind this zone. So, the rate of achieving homogeneous mixing is the higher, the smaller the ratio *D/d*.

The analysis of the velocity and scalar characteristics of the recirculation zone shows that small distortion in mixer geometry produces the strong flow asymmetry. In spite of the flow asymmetry the profile of the mixture fraction across the mixer at the end of recirculation zone is quit uniform. It seems to be realistic that the flow asymmetry enhances the mixing.

The model of the recirculation zone can be considered as a vortex structure that envelops the jet but does not correlate with the jet core. This structure is unsteady and its opposite parts oscillate along the mixer axis in counter phase.

Acknowledgement

The authors are grateful to the staff of the department of the hydrodynamics of Rostock University, headed by Prof A. Leder, particular eng. U. Grebin, for technical assistance in LDA measurements.

The study was supported by Deutsche Forschungsgemeinschaft within the framework of the program SPPP 1141.

References

Barchilon, M., Curtet R., 1964: “Some details of the structure of an axis-symmetrical confined jet with backflow”, Journal of Basic Engineering, Dec. pp. 777-787.

Henzler H.J., 1978: “Investigations on mixing fluids”, Doctor’s Dissertation, RWTH, Aachen, Germany.

Ginevskij A.S., Pochkina K.A., 1967: “The influence of the initial turbulence on the characteristics of submerged axis-symmetrical jet”, Inginerno -fizicheskij zhurnal, No.1, pp.15-19.

Zhdanov V.L., Kornev N.V. and Hassel E., 2004, “LIF investigation of the concentration field in the coaxial mixer”, Lasermethoden in der Strömungsmesstechnik. 12 Fachtagung, 7 – 9 September, Karlsruhe, Germany, pp. 16-1 - 16-8.