

LIF investigation of the concentration field in the co-axial mixer

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Abstract

The experimental results on mixing of two co-axial turbulent flows in a round tube are presented. The inner flow is injected through the central $d = 10$ mm inner dia. tube to the co-flow running into the $D = 50$ mm inner dia. one. The mixing has been investigated at two values of the flow rate ratio $\dot{V}_D / \dot{V}_d = 1.3$ and 5 (where \dot{V}_D is the flow rate through the outer tube and \dot{V}_d is the flow rate through the central tube) and at two Reynolds numbers $Re_d = 10000, 15000$ based on the inner diameter and the bulk velocity of the central tube. The distributions of the concentration, fluctuations concentration across the mixer have been measured by the LIF method within the interval from $x/D = 0.2$ to 9.2. Using these distributions, the integral length and the two-point correlations across the mixer at different cross sections have been calculated. The experiments have revealed homogeneous mixing at $x/D = 9.2$ for the regime $\dot{V}_D / \dot{V}_d = 5$ while this flow state had been already seen at $x/D = 3$ for the regime $\dot{V}_D / \dot{V}_d = 1.3$.

1. Introduction

Mixing, particularly mixing in co-flows has been a subject of investigations for a long time because of their practical applications in many engineering devices such as combustion chambers, injection systems, etc. The jet mixers possess excellent mixing properties due to strong vortices that appear at the jet boundary as a result of the instability of the shear layer. Various jet mixers are classified by Henzler, 1978. In this paper the classical jet mixer consisting of a nozzle of diameter d positioned along the center line of a pipe of diameter D has been considered. The jet mixers of such a configuration are used in chemical engineering for homogenization of streams of different fluids or as chemical reactors to control chemical reactions. These reactions very often are followed by undesirable competitive-consecutive reactions. In the simplest case, the general scheme of these reactions is represented by:



As seen from (1), the undesirable reaction $R + B \xrightarrow{k_2} S$ decreases the production of the primary product R . There are two ways to prevent a decrease in the production of R . Either the species A should be in excess or the mixer should prevent mixing between the product R and the educts B through a proper removal of R from the reaction area. As mentioned (see Tebel et. al., 1988), the jet mixer is an effective device that can reduce undesirable competitive-consecutive chemical reactions due to natural advection of the product R downstream. From the dimensionless analysis it is seen that the characteristics of the jet mixers depend on the following dimensionless parameters: D/d is the diameter ratio, $Re_d = dV_d/\nu$ is the Reynolds number for the nozzle flow, Sc is the Schmidt number, \dot{V}_D / \dot{V}_d is the ratio of the co-flow rate to the injected one from the nozzle, ρ_d / ρ_D is the fluid

density ratio. In the no isothermal case the Prandtl number and the temperature ratio $(T_D - T_d)/T_D$ are the additional parameters.

The most important parameter influencing the mixing is the ratio \dot{V}_D/\dot{V}_d . It is responsible for two possible regimes of jet mixers, see Henzler 1978 and Korischem 1987. If the quantity $(1 + \dot{V}_D/\dot{V}_d)$ is larger than the ratio D/d , then the flow pattern in the pipe is a similar to that of the free jet. When $1 + \dot{V}_D/\dot{V}_d < D/d$, a co-flow separates near the pipe walls behind the nozzle and the recirculation region is generated. This recirculation zone enhances drastically the mixing so that a homogeneous state is reached after four- five pipe diameters downstream of the nozzle.

A mixedness degree is the integral criterion for the homogenization in the jet mixers. Following Danckwerts 1952, it can be defined for each cross-section of the mixer as

$$\alpha = 1 - \frac{\int_S (f(x, r, \theta) - f_{av}(x))^2 r dr d\theta}{\int_S (f(0, r, \theta) - f_{av}(0))^2 r dr d\theta} \quad (2)$$

where $f_{av}(x) = \frac{1}{S} \int_S f(x, r, \theta) r dr d\theta$; S is the area of the cross section and f is the concentration of the fluid A ejecting from the nozzle into the coflow B . Integral criterion (2) characterizes the macromixing. The accurate modeling of the chemical reactions needs quantitative information on the spatial distributions of the concentration $f(x, r, \theta)$, fluctuations $\overline{f'^2(x, r, \theta)}$ as well as on the integral length scale and the autocorrelation function across and downstream of the mixer. The present work is aimed at getting these data and investigating the influence of Re_d , \dot{V}_D/\dot{V}_d and $(T_D - T_d)/T_D$ on the above-mentioned parameters and mixing criteria.

2. Experimental set up

Experiments were conducted in a water channel (Fig.1).

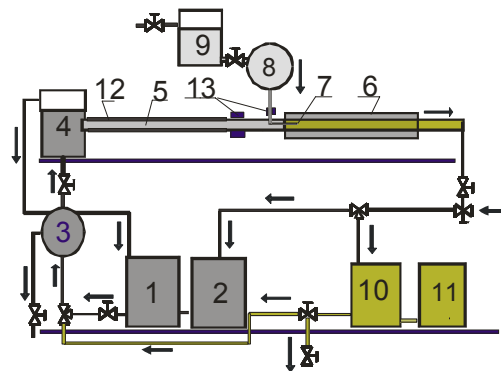


Fig. 1: The scheme of the water channel. 1, 2, 4 – water vessels; 3,8 – pumps; 5 – steel tube; 6 – test section; 7 – inner tube of the mixer; 9, 10, 11 – rhodamin solution vessels; 12- electric heater; 13 – flow rate meters

The water was pumped from vessels 1 and 2 by pump 3 to vessel 4 and from there was charged to steel tube 5. The length of this tube was about 5 m, so the turbulent flow developed before test section 6. Tube 5 was connected with a Perspex tube of the same

inner diameter ($D = 50$ mm) at the entrance of the test section. The tube length was 1000 mm and this tube was installed in a Perspex rectangular box filled with water to reduce refraction effects. Horizontally located inner tube 7 of 600 mm in length ($d = 10$ mm) was placed symmetrically along the axis of the Perspex tube. A rhodamin 6G water solution was injected from vessel 9 through inner tube 7 by pump 8. The flow rates were controlled by flow meters 13 (ultrasound meter FLUXUS AM7207). In experimental measurements, to prevent changes in the flow background intensity due to substitution of water by the rhodamin solution, the mixture behind the test section was collected in vessels 10 and 11. The electrical heater 12 was installed on the steel tube 5 and was used to investigate the influence of the co-flow temperature on the mixing process.

2.1. The optical set-up. Laser-induced fluorescence (LIF) was used for measuring instantaneous rhodamin 6G concentration distributions in the turbulent flow field of a co-axial mixer. The concentration of a fluorescence dye was determined by measuring the intensity of light emitted by rhodamin molecules excited by a light source with a known power. The light source was an impulse ND: YAG laser ($\lambda = 532$ nm, Continuum, PREC II 8000). The repetitive rate of a laser beam was 10 Hz and the minimal impulse duration was 9 ns. The exit laser beam was transformed to the light sheet by an optical unit that consisted of one cylindrical lens ($f = 270$ mm) and two plane-convex lenses ($f_1 = 300$ mm, $f_2 = 200$ mm), respectively. The thickness of the laser sheet across the mixer was 0.7 mm and changed around 30μ across the diameter. The light sheet was designed in the vertical plane through the mixer centerline. The optical unit was moved along the test section to measure the concentration at different distances from the nozzle inner tube.

The emitted light was imaged onto an intensified CCD camera (PI-MAX, Roper Scientific) supplied with a lens ($f = 50$ mm, F/1.2, Nikkor) and a sharp cut-off filter ($\lambda = 600$ nm, Edmund Industrie Optic GmbH). The camera was triggered by the laser and was positioned at a right angle to the light sheet. In experiments the camera followed the light sheet coordinate so that their common positions were the same in each cross-section.

2.2. Data processing. The original software (WinSpec-32) allows us to measure the intensity of a full-scale flow image (1024×256 pixel) as well as the intensity of the region of interest (ROI) that was chosen in our experiments as a strip of one pixel length in the flow direction and 256 pixel width across the mixer. Owing to this choice, the time to read and digitize a signal decreased drastically and the sampling time of one frame was about 1 sec. For each measurement location 300 frames with a total measurement time of 5 min were obtained and averaging for each pixel. The correction for the dark current was subtracted for every frame.

Calibration measurements were done to compensate different sensitivity of CCD pixel to the emitted light due to changes in the angle of the accepted light. The calibration box being a copy of the test section was filled with a uniform concentration dye, and 100 frames were recorded and then averaged at each pixel. From these measurements the individual correction coefficients for each pixel were determined. As soon as there was a linear dependence between the intensity fixed by pixel and the concentration value in the investigated region (concentration rhodamin solution was changed from $c_{\text{inlet}} = 0.005$ up to 0.03 mg/l) at a constant laser power (mean value 300 mW), these corrections were the same for different concentrations.

The fluorescence intensity (I) is the function of the laser intensity (I_0), the dye concentration (c), the coefficient absorption (ε), and the quantum efficiency (ϕ)

$$I = I_0 \cdot c \cdot \varepsilon \cdot \phi$$

If I_0 is known, ε and ϕ are constant, then the emitted intensity is only the function of dye concentration. The laser light intensity along the laser beam decayed due to light accumulated by a rhodamin molecule. As a result, the emitted light should be also reduced.

Light beam attenuation is the stronger, the higher the concentration. Our calibration curves made for different concentrations at a constant laser power did not show systematic variations between them that could be a sequence of the pore influence of the absorption effect, so no correction for this phenomenon was made. This is consistent with the investigations of Arcoumainis et al., 1990, where it was emphasized that the signal intensity was independent of the optical length while the concentration was less than 0.08 mg/l.

The absolute values of the intensity and the fluctuations of this intensity increase with the concentration at the same laser power (Fig. 2). The variations of the noise fluctuations with concentration were determined by the calibration procedure and were used for correcting the concentration fluctuations measured in experiments.

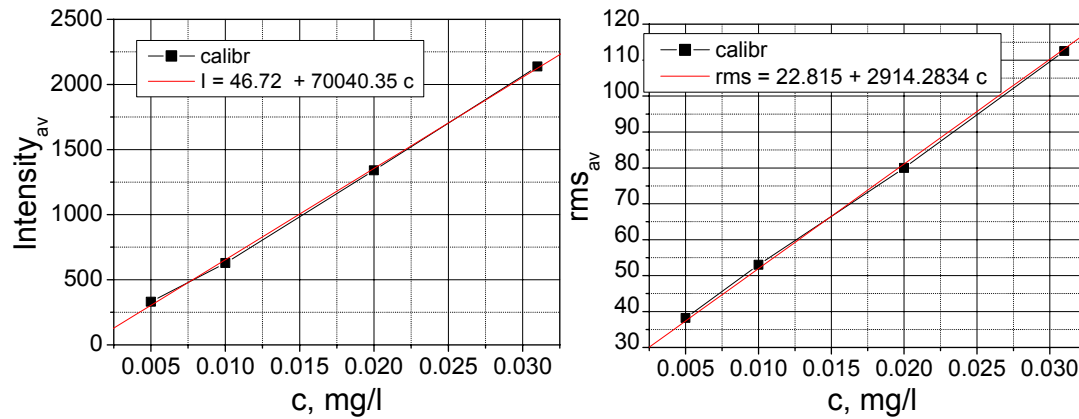


Fig. 2: Variations intensity and intensity fluctuations at the same laser power beam for different dye concentrations

The concentration distributions have been obtained by normalizing the local intensity (after the corrections) with the maximal intensity on the axis of the nozzle at the first cross section ($x/D = 0.2$). So our results present the distributions of the relative fraction of the initial concentration or mixture fraction and its rms. criteria.

2. Results

Concentration measurements were made for two values of the ratio $\dot{V}_D / \dot{V}_d = 1.3, 5$ and for the Reynolds numbers $Re_d = 10000, 15000$. The first flow rate ratio $\dot{V}_D / \dot{V}_d = 1.3$ corresponds to the flow with a recirculation zone (regime A) whereas the second one relates to the flow of the jet type (regime B). The temperature influence has been investigated for both regimes at the $Re_d = 10000$. The temperature ratio between the co-flow and the injected fluid was $(T_D - T_d) / T_D = 0.0$ and 0.12 ($\Delta T = 35^\circ\text{C}$). The development of the concentration field for both regimes downstream of the flow along the pipe axis has shown that the mixing was quite different (Fig.3).

For the regime A the concentration along the flow axis changes in the interval $0 \leq x/D \leq 3$ and then was practically constant $f \sim 0.5$. The values of the rms mixture fraction along the pipe centerline has a maximum $f'/f_0 = 0.1$ within $1.2 \leq x/D \leq 2.2$ then they decrease in twice and vary insignificantly behind the distance $x/D = 5.2$.

The concentration decreases stronger and in a wider interval behind the nozzle for regime B. It can be expected that the mixture fraction reaches some constant level around $f \sim 0.2$ at $x/D > 9.2$. The level of the rms mixture fraction is higher than the one in regime A. The values of the rms mixture fraction that are nearly zero in the nozzle exit plane increase up to $f'/f_0 = 0.16$ at $x/D = 3.2$ and then decrease rather slowly reaching the value of $f'/f_0 = 0.1$ at $x/D = 9.2$.

As seen, the Reynolds number and the co-flow temperature have no influence on the behavior of the mixture fraction and the rms mixture fraction.

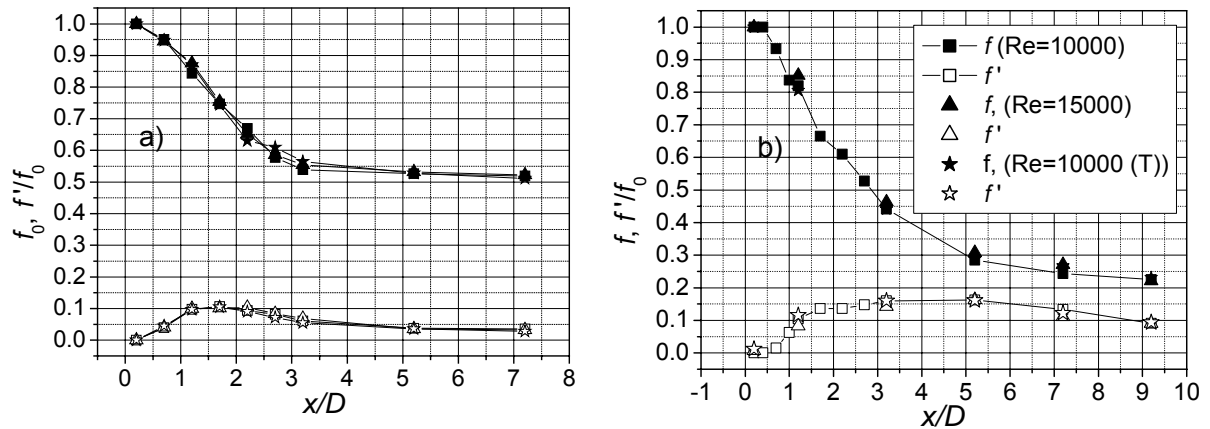


Fig. 3: Mixture fraction and rms mixture fractions variations along the mixer axis for regimes A (a) and B (b)

The dimensionless profiles of the mixture fraction and the rms mixture fraction for both investigated regimes detail a difference in the flow structure for the considered regimes (Fig.4).

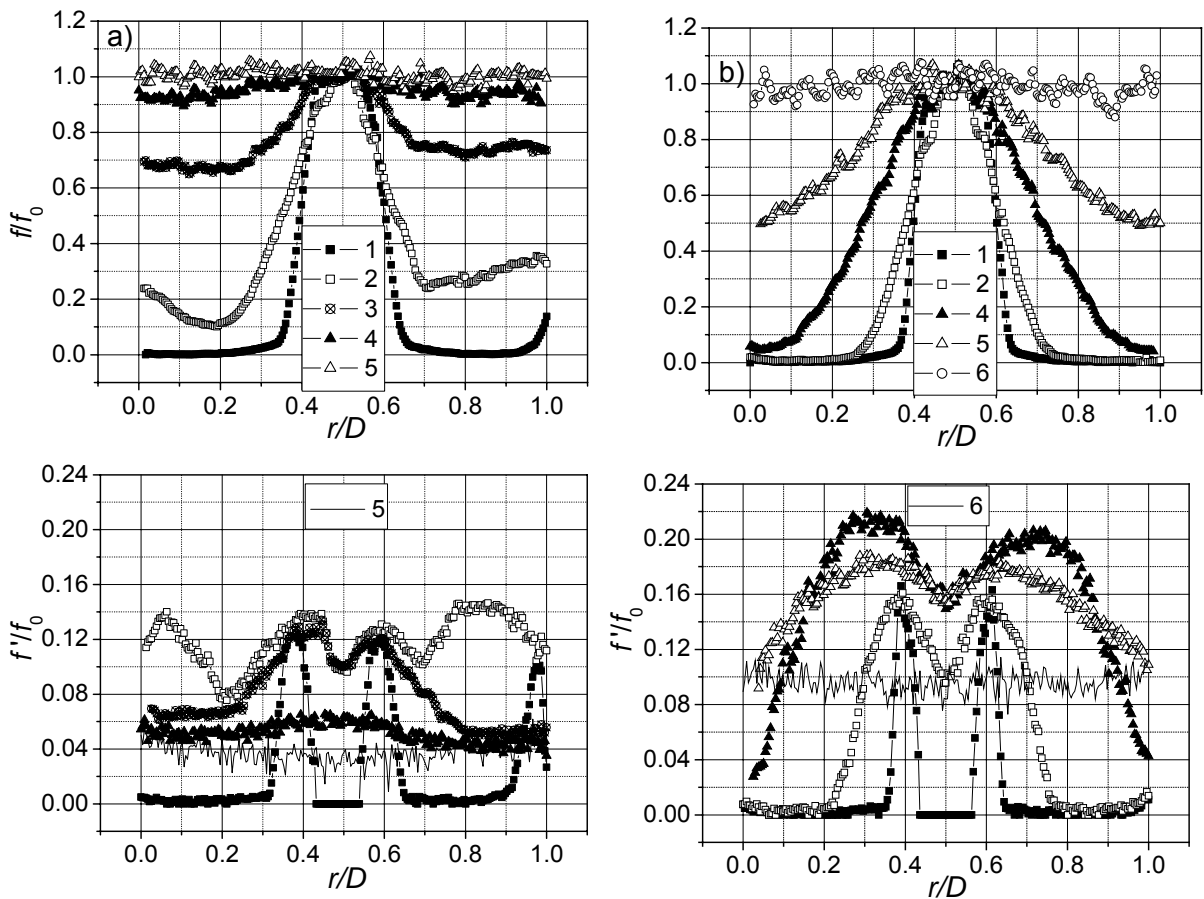


Fig. 4: Mixture fraction and rms mixture fraction profiles for the regimes (a) $\dot{V}_D / \dot{V}_d = 1.3$ and (b) $\dot{V}_D / \dot{V}_d = 5.0$: 1 – $x/D = 0.2$; 2 – 1.2; 3 – 2.2; 4 – 3.2; 5 – 5.2; 6 – 9.2

It should be noted that the mixture fraction increases near the mixer walls just behind the nozzle for regime A (Fig.4a). This tendency is developing downstream so that the nearly

homogenous mixture has been already presented at the distance $x/D = 3.2$. The same mixture state has been observed only over the cross section $x/D = 9.2$ for regime B. The profile asymmetry (regime A) seems to be due to a certain flow asymmetry in the mixer. The concentration increase at the mixer walls causes the maximum rms mixture fraction to reduce due to a decrease in the concentration gradient across the mixer. The mixture fraction growth close to the pipe walls is due to three dimensional unsteady separations at the mixer walls behind the nozzle when $\dot{V}_D / \dot{V}_d = 1.3$. These separations are responsible for recirculation region generation that enhances the mixing. This region occupies the interval $0.2 < x/D < 2.7$ as it is seen from the development of two-point correlation distributions R_f (Fig. 5).

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

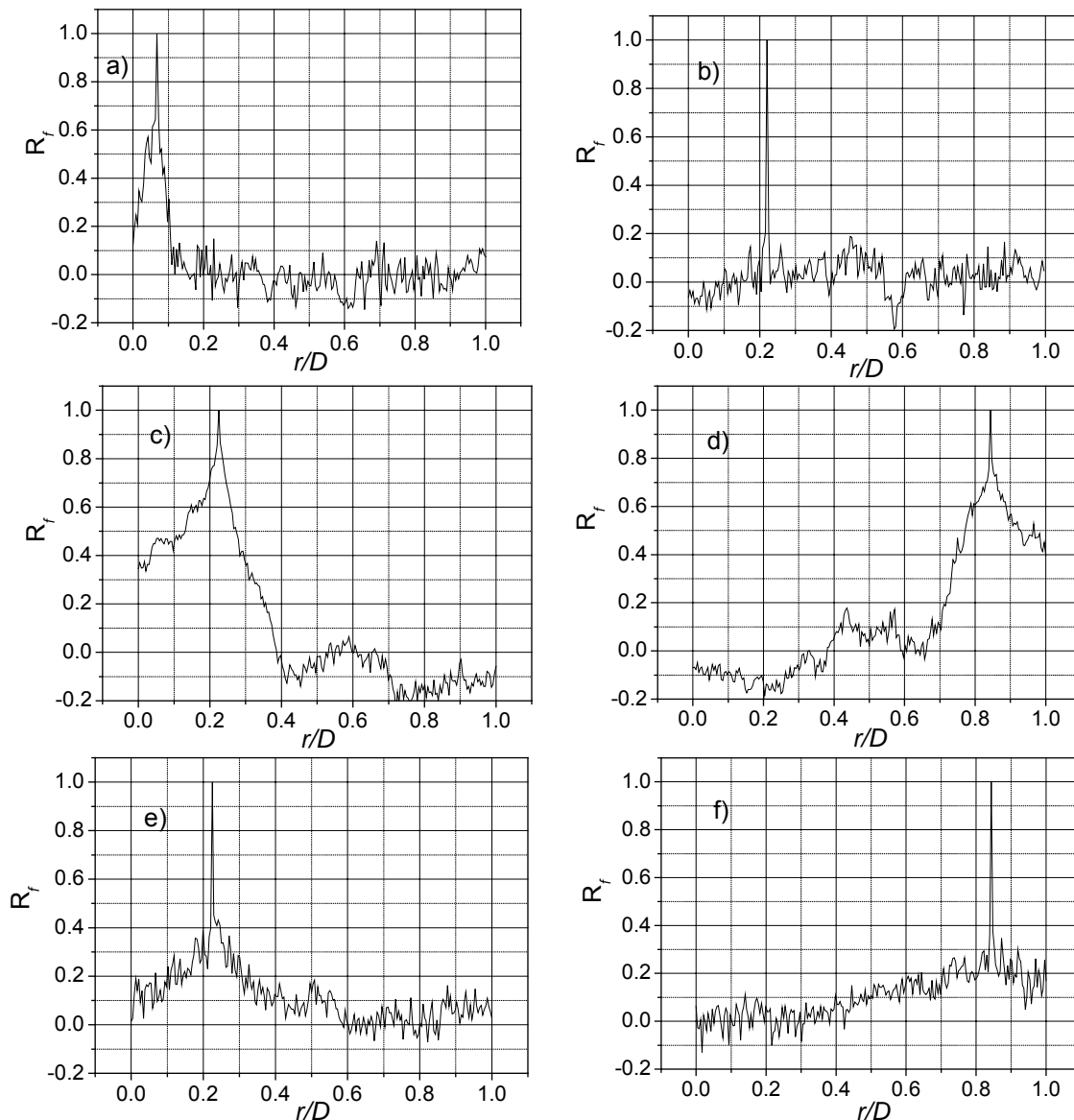


Fig. 5: The two –point correlation across the mixer at the different distance from the nozzle for regime A: a) $x/D = 0.2$; $r/D = 0.07$; b) $x/D = 0.2$; $r/D = 0.22$; c) $x/D = 1.7$, $r/D = 0.22$; d) $x/D = 1.7$, $r/D = 0.84$; e) $x/D = 2.7$, $r/D = 0.22$; f) $x/D = 2.7$, $r/D = 0.84$

The autocorrelation functions (Fig. 5) reveal the vortex structures observed in the flow. Large vortices arising due to separation are seen in the region close to the pipe wall (Fig.

5a, c, d). In the flow core the vortex structures are smaller. The features of these vortices are best evident at the distance $x/D = 1.7$. The autocorrelation functions calculated for second regime B are very close to the common ones known for the free jet configuration.

The comparison of the integral length across the mixer for both regimes has shown that the maximum integral length is about twice times larger for regime A (Fig.6).

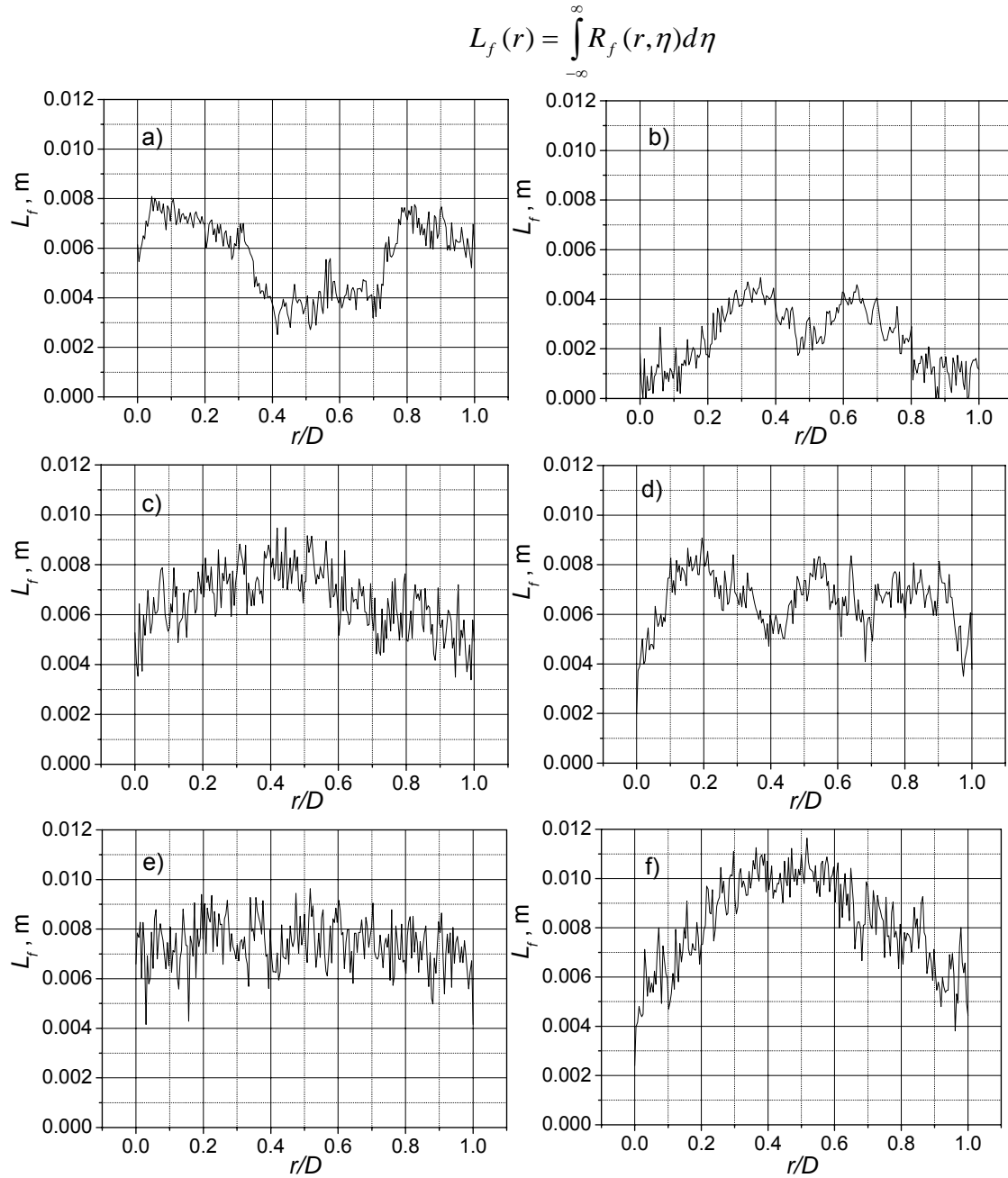


Fig. 6: Integral length variations across the flow in the mixer: a, c, e) $\dot{V}_D / \dot{V}_d = 1.3$; $x/D = 1.7, 3.2; 7.2$, respectively; b, d, f) $\dot{V}_D / \dot{V}_d = 5.0$; $x/D = 1.7; 3.2; 7.2$, respectively

The maximal value of the integral length is the same at all investigated distances behind the nozzle for regime A whereas it increases downstream for regime B.

The Danckwerts criterion (α) shows that the homogeneous concentration across the flow (completed mixing) is attained at the distance $x/D = 3.2$ downstream of the nozzle for regime A. On the contrary, the mixing process comes to an end only behind the distance $x/D > 7.2$ for regime B: $\dot{V}_D / \dot{V}_d = 5.0$ (Fig.7). There is no essential influence of the Reynolds

number and the temperature on the mixing within the range of the investigated flow parameters.

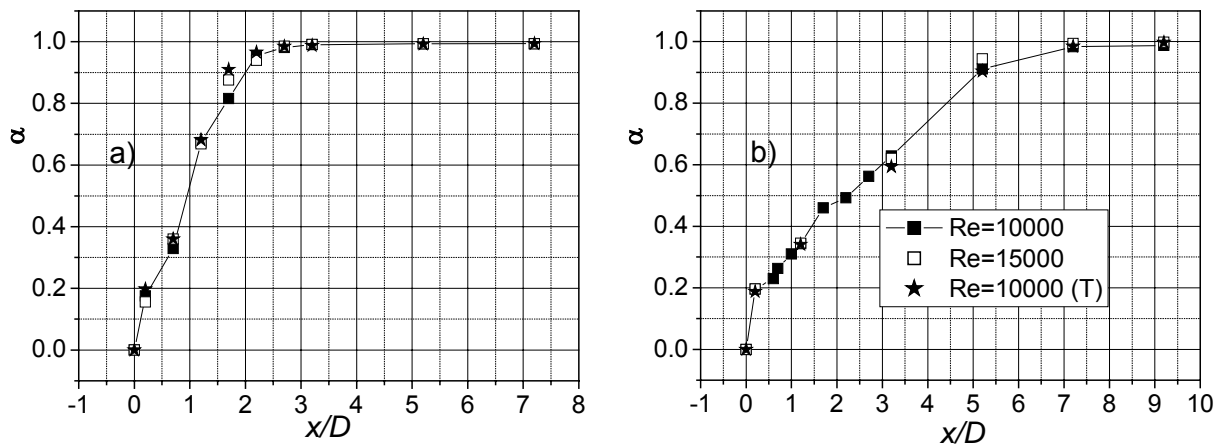


Fig. 7: Danckwerts' criterion variations along the mixer at different Reynolds numbers and under the temperature influence: a) $\dot{V}_D / \dot{V}_d = 1.3$; b) $\dot{V}_D / \dot{V}_d = 5.0$

Acknowledgement

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

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