On flow fluctuations in a static mixer

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ABSTRACT

Systematic experimental investigations of the flow filed for liquids inside static mixers have not yet been found in the open literature. Only fragmentary information was published on the flow close to the mixer exit. In particular, no data for the transitional flow range is available. The presented study aims at shedding more light on the liquid flow instabilities occurring inside a static mixer. Such an experimental evidence should enhance both our fundamental knowledge of the mixing mechanism and would also provide a basis for validation of momentum transfer simulations by Computational Fluid Dynamics (CFD) codes.
The measurements were carried out for an SMX static mixer using a 1D laser Doppler velocimeter with the IFA 750 signal processor delivered by TSI Inc. The SMX mixer constituted the main part of a circulation system and had the internal diameter of 80 mm. The flow rate through the mixer was kept constant by means of a special control system with an in-line electromagnetic meter. The straight, vertical tube of the mixer had the length of about 2,4 m and contained the test section made of Perspex. Six SMX inserts were located inside the test tube. In order to ensure fully developed flow conditions, the main velocity data were collected for the fifth insert downstream and also well upstream the first insert for checking the inlet conditions. The test fluids were Newtonian solutions of glucose syrup of varied concentration. The velocity data were taken for the axial component at three levels of Reynolds number, Re, of 40, 640, 2560. The total number of individual Doppler bursts used in the analysis was from about 9846 to 15970. This corresponded to the mean acquisition rate from approximately 4 Hz to 35 Hz.
The velocity fluctuations were also analysed as the energy spectrum in the frequency domain after processing the data with the help of the Fast Fourier Transform. The spectral analysis allowed the authors to conclude that the spectra were very similar in corresponding measurement points of the two insert halves, irrespective of Reynolds number applied. Only a small effect of the radial position of the measurement point was obtained. The onset of the transitional flow with systematic velocity fluctuations was noticed as early as at Re=40 whereas within the range of Re from 640 to 2560 the flows exhibited features typical for the turbulent flow regime with dominating random fluctuations.

INTRODUCTION

Systematic experimental investigations of the velocity field for liquids flowing inside static mixers have not been found in the open literature. Only fragmentary information was published on the flow close to the mixer exit. In particular, no data for the transitional flow range is available. The presented study aims at shedding more light on the Newtonian liquid flow instabilities occurring inside a static mixer. Such an experimental evidence enhances both our fundamental knowledge of the flow and mixing mechanisms and also provides a basis for validation of momentum transfer simulations by Computational Fluid Dynamics (CFD) codes.
A commonly adopted criterion applied in the literature for validating the CFD flow simulations in static mixers is the agreement of the simulated pressure drop with that measured experimentally, e.g. in Hobbs et al. (1998), Hobbs and Muzzio (1997), Rauline et al. (1998). However, in an earlier study, Adamiak and Jaworski (1999) found that such the agreement does not guarantee that the simulated flow field has the same characteristics as the experimental one. The discrepancy between the modelled mean velocities and the experimental from LDV was found maximum in the transitional flow range.
A general conclusion, drawn from earlier investigations carried out for a Kenics static mixer (Peryt et al., 2001), is that velocity fluctuations were most probably caused by flowing vortex structures. A static mixer of the SMX type, similar to that manufactured by the Sulzer and Koch companies, was chosen for this study and the spectral analysis of LDV data was destined to investigate the flow instabilities inside the mixer. This study was induced by earlier measurements of velocity fluctuations, which suggested that clear indications of the transitional flow occurred at superficial velocity Reynolds number, Re, of about 640, thus a relatively wide Re range was chosen for this study, well above and below that value (Jaworski et al., 2001).

Examples of the spectral analysis of LDA data using the FFT transform were published by Kaleva et al. (2000) and by Gjelstrup et al. (2000). However, in those papers the FFT analysis was applied to solving different problems than the one described in this paper.

MEASUREMENT METHODOLOGY

The SMX mixer constituted the main part of a circulation system (Fig.1) and had the internal diameter of 80mm. The flow rate through the mixer was kept constant by means of a special control system 3 with an in-line electromagnetic meter 4. The straight, vertical tube 2 of the mixer had the length of about 2.4m and contained the test section made of Perspex of about 1 m length. Six SMX inserts were located inside the test tube (Fig. 2). In order to ensure fully developed flow conditions, the main velocity data were collected for the fifth insert downstream. The inlet conditions to the insert section were also tested well upstream the first insert. The process fluids were Newtonian solutions of glucose syrup of varied concentration, from 70% to 45% for Re=40 and 2560, respectively. Density of the syrup solutions varied from 1295 to 1176 kg/m^3 and its dynamic viscosity varied from 0.0861 to 0.0063 Pa s. The velocity data were taken only for the axial component at three levels of Reynolds number, Re, of 40, 640 and 2560. The mean superficial axial velocity, which was used for calculating Re, was chosen in the range from 0.04 to about 1.2 m/s. Eight measurement points for each Re level were chosen at characteristic locations within the fifth insert, in the radial distance from the mixer wall of either 6mm (R=0.034m) or 14mm (R=0.026m).

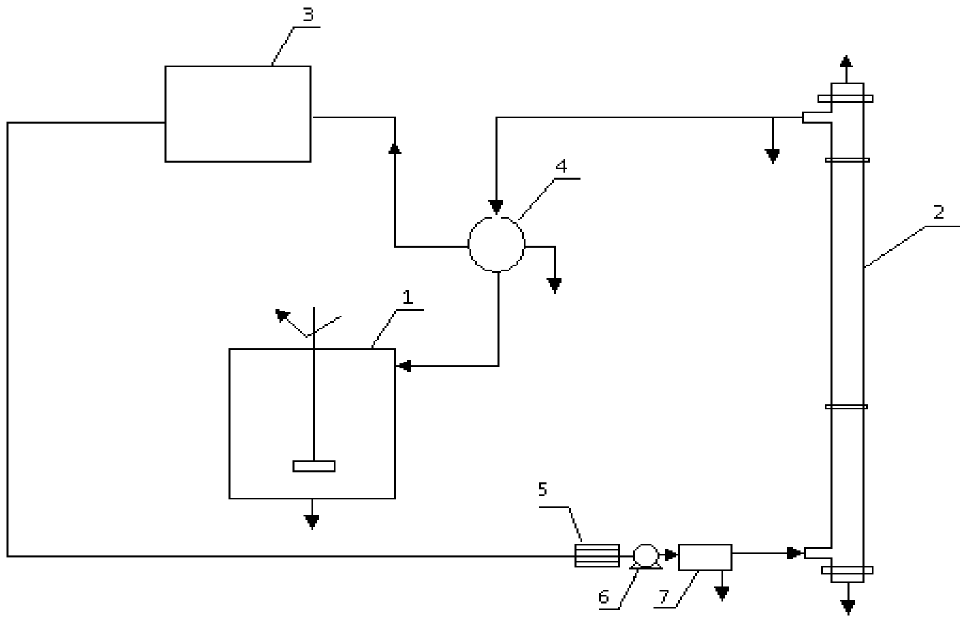


Figure 1. The experimental rig. 1- storage vessel, 2 – static mixer tube with test section, 3 – flow control unit, 4 – electromagnetic flow meter, 5 – motor, 6 – helical pump, 7 – pulsation damper.

The measurements were carried out for the SMX static mixer using a 1D laser Doppler velocimeter with the IFA 750 signal processor (digital burst correlator) and the FIND software delivered by TSI Inc. The meter was equipped with a 500 mW Argon ion laser gun (Omnichrome), a multicolour beam separator ColorBurst model 9201, a fiber optics probe model 9800 and a multicolour signal receiver Color Link model 9230. The focal length of the probe exit lens in air was 129.485 mm with the half-angle of beam intersection of 10.821° and the wavelength of the green beam was 514.5 nm. The applied frequency shift depended on the Re level and was set to 10 kHz for Re=40 and to 100 kHz for the two other Re levels. The upper and lower filter frequencies were set respectively to 10 kHz and 100 kHz for Re=40 and to 30 kHz and 300 kHz for the two higher Re levels. The following processor setup was chosen for the reported measurements: random mode with time stamp, single measurement per burst, burst transit time weighing, processor control target efficiency of 55% and medium signal-to-noise ratio. The flow was seeded using the Dantec PSP-5 polyamide particles of the mean size of 5 µm.

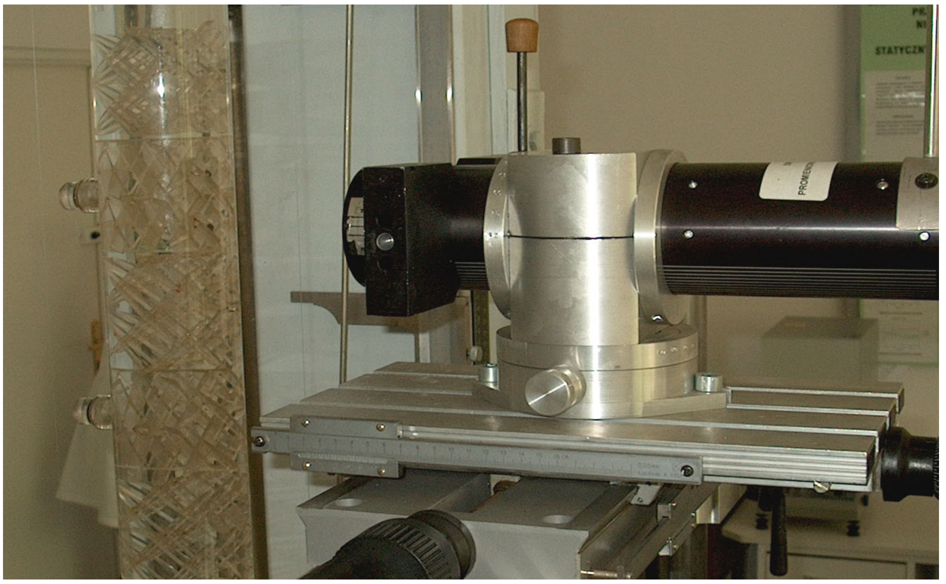


Figure 2. The LDV probe with the mixer test section

The axial velocity measurements were carried out for three levels of Reynolds number chosen at 40, 640 and 2560. The volumetric flow rate in the mixer corresponded to 0.61, 2.12, 3.10 m^3 /h for the three Re levels. The LDV readings were taken in the middle of the lower insert height (L1 position) and in the middle of the upper insert height (L2). The fiber optics probe axis was always aligned perpendicularly to the main vertical axis of the mixer tube and the insert (Fig. 3). The mixer tube was rotated to form an angle of either 0º or 90º of the probe axis with the direction of the horizontal square cross-section channels of the fifth SMX insert (Fig.3).

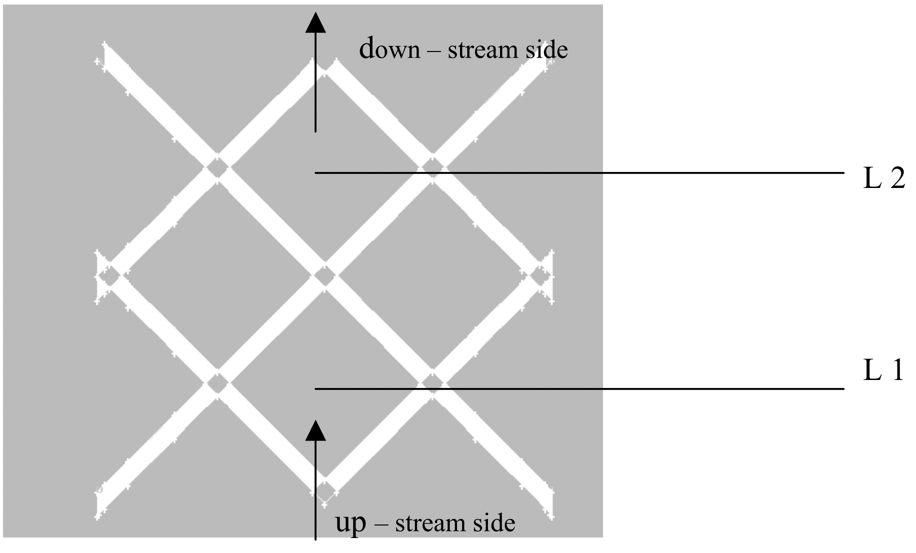


Fig. 3. The measurement positions inside the SMX insert, angle 0 degree

The experiment was conducted at two radial positions, R, for each of the two axial positions (L1 and L2) and of the two angular alignments. The two R values were chosen to be the radial distances of either 0.034m or 0.026m from the tube axis. The total data acquisition time ranged from about 3000 s to 1600 s for Re=40 to 2560, respectively. The data acquisition rate also depended on Re and on the radial distance R and fell in the range of 4 Hz to 35 Hz. The efforts to substantially rise the acquisition rate by heavier flow seeding did not succeed. The total number of individual velocity samples collected at a given location slightly depended on the acquisition rate and the data number ranged from 39918 to 56405 points.

RESULTS

The raw LDV data obtained for the three Re values were processed with the help of the Fast Fourier Transform (FFT) to make their spectral analysis in the frequency domain possible. The basic sample size chosen contained 1024 signals, thus the total number of the transformed data into the frequency domain was a multiple of 1024. For instance, for the total sample size of 30840 Doppler bursts, 30x1024=30720 individual observations were taken to the FFT analysis.

The processed results were further analysed separately for each of the three Re levels and compared for the two angular alignments and two axial positions, L1 and L2. However, the figures in this report present graphically data only for the first axial position, L1 as equivalent graphs for the L2 position were almost identical. Different scale was applied in the figures for the fluctuating energy, which was significantly lower for Re=40 than for the other two Re levels.

Velocity fluctuations for Re=40

The FFT transformation of the LDV data resulted in one-dimensional fluctuating energy density, E [m^2/s], which was plotted against the fluctuation frequency, f [Hz]. Analysis of the energy spectrum obtained for the glucose syrup at Re=40 and the angular position of 0 degree revealed that the energy density level was rather low and ranged from about 10^{-6} to 10^{-3} m^2/s and from $6 \cdot 10^{-6}$ to $4 \cdot 10^{-4}$ m^2/s, for R=0.034m and R=0.026m, respectively (Figs. 4a, 4b). One of the important findings was the detection of characteristic peaks occurring at the frequencies, f, of approximately 1.5, 3 and 6 Hz (Fig. 4a), in the mid-height both of the first SMX insert half (L1) and also of the second (L2) close to the wall, i.e. for the radial distance of R=0.034m. The peak frequencies appear roughly at harmonic intervals. With the increasing distance from the mixer wall the peak extent and intensity were decreasing (Fig. 4b). The LDV data acquisition rate achieved was not high enough to draw firm conclusions on the peak number at higher frequencies. However, the results clearly confirm the existence flow instabilities and systematic fluctuations inside the SMX insert, presumably due to formation of vortex structures.

At the mid-height of the insert first half (position L1) and for the angular position of 90 degrees, the fluctuation energy density, E, was in the range from 10^{-5} to 10^{-3} m^2/s or from 10^{-6} to 10^{-4} m^2/s for R=0.034m or R=0.026m, respectively (Figs. 5a and 5b). In addition, the LDV data acquisition rate was about three times lower for the smaller radial distance, R, than for the position closer to the tube wall. This is why the power spectrum for R=0.026m ends at smaller frequencies than for R=0.034m (cf. Figs. 4a vs. 4b and 5a vs. 5b).

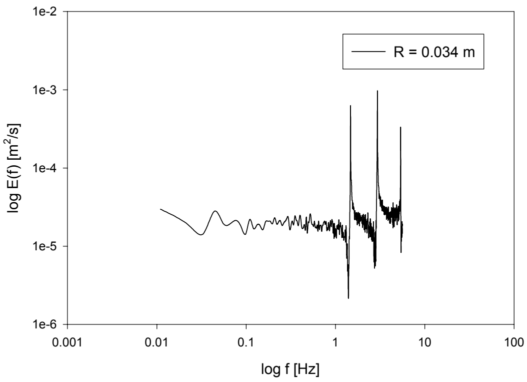


Fig. 4a. One-dimensional fluctuation energy spectrum, position L1, Re=40, α=0°, R=0.034m

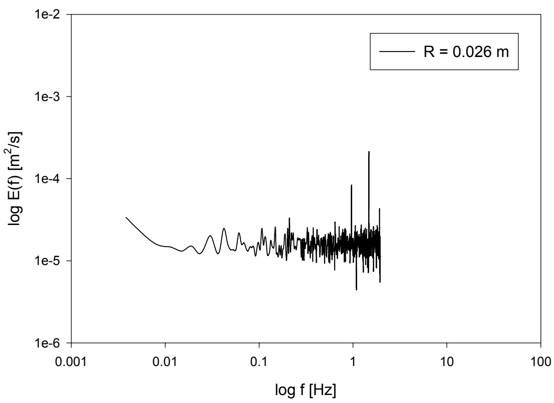


Fig. 4b. One-dimensional fluctuation energy spectrum, position L1, Re=40, α=0°, R=0.026 m

In the upper insert channel (position L2), the spectral density ranged also from 10^{-5} to 10^{-3} m^2/s or from 10^{-6} to 10^{-4} m^2/s for R=0.034m or R=0.026m, respectively (Figures not shown). Very similar peaks appeared in the energy spectrum as for their counterparts in the lower insert channel. The rms fluctuation velocities normalised by the superficial liquid velocity were about 1.70% for the L1 position and 1.76% for L2, irrespective of the angular position in the SMX insert. Such a rms value can be regarded as insignificant and may have been mainly caused by small fluctuations of the mean flow through the static mixer.

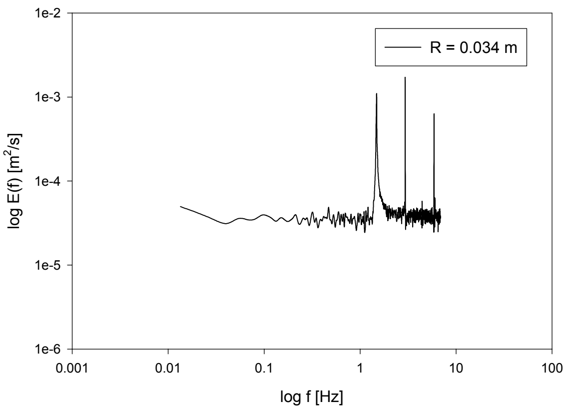


Fig. 5a. One-dimensional fluctuation energy spectrum, position L1, Re=40, α=90°, R=0.034m

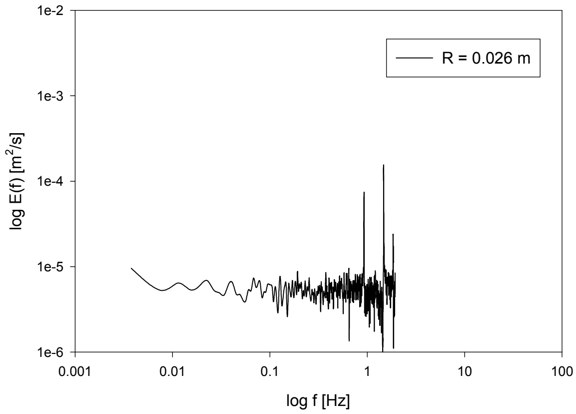


Fig. 5b. One-dimensional fluctuation energy spectrum, position L1, Re=40, α=90°, R=0.026m

Velocity fluctuations for Re=640

The fluctuation energy values, E, for the L1 position at Re=640 ranged from 0.7 to 1 m^2/s or from 0.05 to 0.5 m^2/s, respectively for the radial positions R=0.034m or R=0.026m. Similar values were obtained in the L2 axial position, i.e. in the second insert half, with E= 0.5 ÷ 0.8 m^2/s at R=0.034m. Contrary to those for Re=40, the spectra did not show clear peaks at the two axial positions, L1 and L2, neither at R=0.034m nor at R=0.026m.
However, the normalized rms fluctuating velocity significantly increased, compared with that for Re=40 by about 20 times, and in average it was as high as about 1/3 of the superficial axial velocity. The mean figures of the rms fluctuation velocities of the glucose syrup were 28% and 42% for the L1 and L2 positions, respectively. Such rms values along with the energy spectra without clear peaks (Fig. 6a, 6b) suggest that there were random velocity fluctuations present.
An unexpected sudden decrease in the energy plot for R=0.026m was obtained (Fig. 6b) close to the frequency of 0.01 Hz, followed by a broad energy band at higher frequencies. A possible explanation to it could be some instability in the flow control during the long period of data collection.

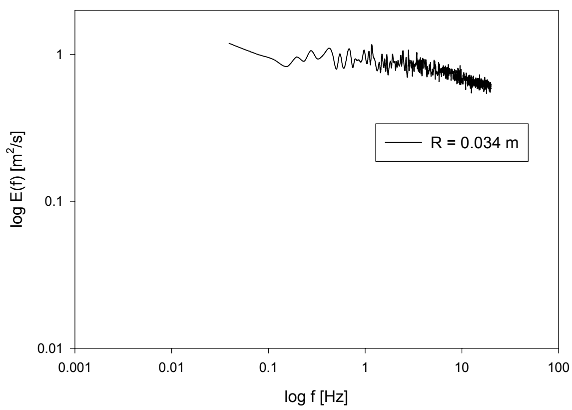


Fig. 6a. One-dimensional fluctuation energy spectrum, position L1, Re=640, α=0°, R=0.034m

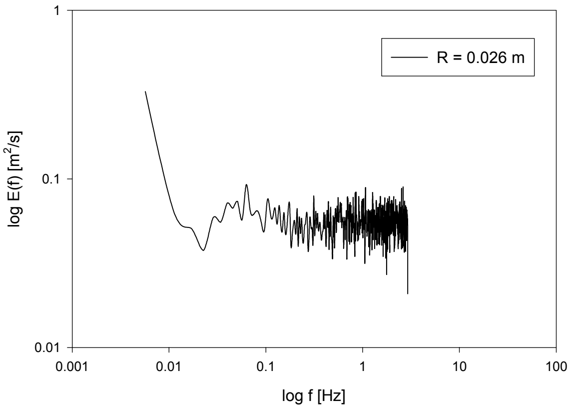
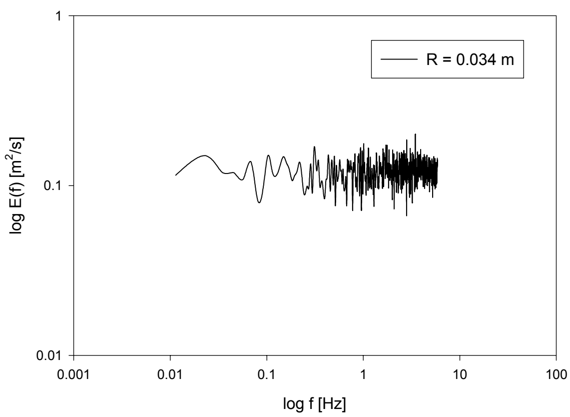


Fig. 6b. One-dimensional fluctuation energy spectrum, position L1, Re=640, α=0°, R=0.026m



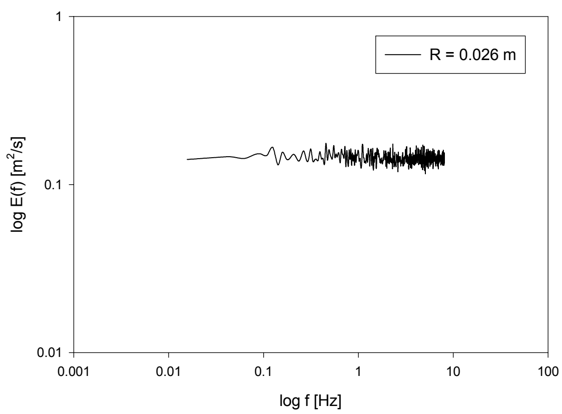
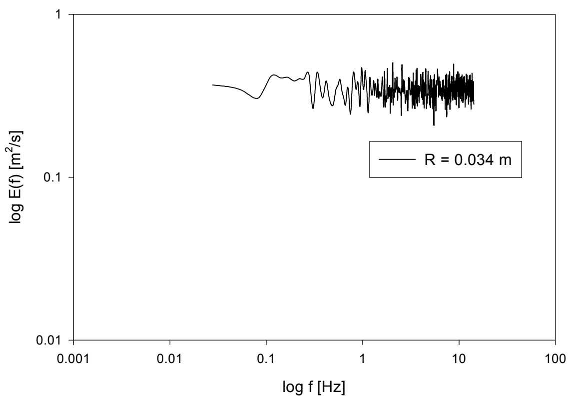


Fig. 7a. One-dimensional fluctuation energy spectrum, position L1, Re=640, α=90°, R=0.034m

Fig. 7b. One-dimensional fluctuation energy spectrum, position L1, Re=640, α=90°, R=0.026m

Velocity fluctuations for Re=2560

The fluctuation energy density for the first insert half (position L1) and the angular position of 0 degree ranged from 0.3 to 0.7 m^2/s and from 0.06 to 0.2 for R=0.034m and for R=0.026 m, respectively (Figs. 8a and 8b). In addition, at the radial position R=0.026m the energy spectrum had a wider scatter range, which also happened at Re=640. For the second insert half (position L2), the energy density was similar, e.g. in the range from 0.4 to 0.9 m^2/s for R=0.034m. The spectra E(f) were almost identical for the first insert half and for the second, which again confirms symmetrical flow characteristics for the two insert halves.



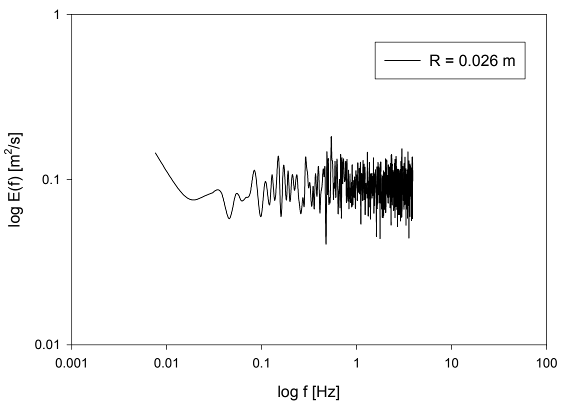


Fig. 8a. One-dimensional fluctuation energy spectrum, position L1, Re=2560, α=0°, R=0.034m

Fig. 8b. One-dimensional fluctuation energy spectrum, position L1, Re=2560, α=0°, R=0.026m

With the change of the measurement point from the angular position of 0 to 90 degrees, the fluctuation energy density slightly increased (Figs. 9a and 9b). For example, at the L1 axial position and the angular probe position of 90º the energy was in the range of 0.6 to 0.9 m^2/s and 0.05 to 0.2 m^2/s for R=0.034m and 0.026m, respectively. For given R and α values the energy spectra had a very similar shape. For the radial distance of R=0.026m and both in the upper and lower insert halves, the energy spectrum showed wide scatter, which is difficult to interpret at this stage. One of possible causes can be instability of the flow control.
The fluctuating velocity magnitude depended on the measurement point location. Thus, in the insert first half and at α=0 the standardized rms velocity was 37% or 45% respectively for R=0.034m or 0.026m. However, in the second half and at the same angle the corresponding rms values were as high as 62% and 84%. A different trend was detected for the angular probe location of 90 degrees with the respective rms values of 63%, 35%, 65% and 60%. The results confirm that, similar to the situation for other Re levels, no general rules can be applied to the fluctuation levels.

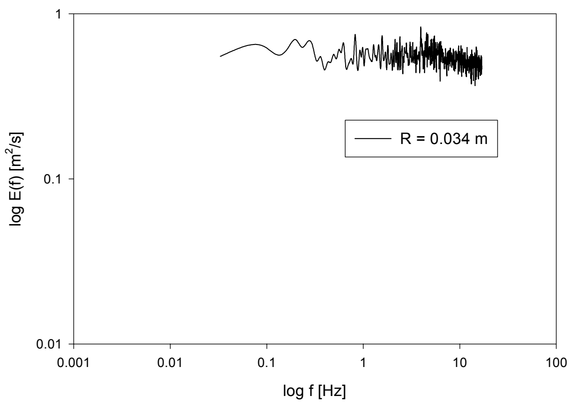


Fig. 9a. One-dimensional fluctuation energy spectrum, position L1, Re=2560, α=90°, R=0.034m

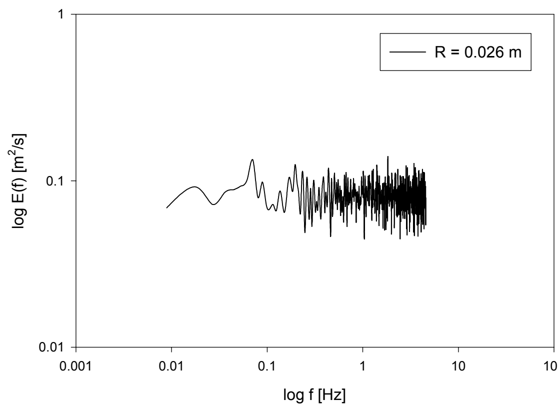


Fig. 9b. One-dimensional fluctuation energy spectrum, position L1, Re=2560, α=90°, R=0.026m

Inlet flow data

The spectral analysis of the LDV data collected at points located inside the SMX insert left an open question regarding the origin of irregularities in the fluctuating energy plots. It was decided to check whether the inlet mean flow conditions to the first mixer insert were close to the typical conditions for the Re values chosen. For instance, whether the energy spectrum exhibits for Re= 640 and 2560 the descending part at higher frequencies and whether clear peaks are present in the spectrum. The measurements were taken at the distance of 0.160m upstream the first SMX insert, i.e. at two tube diameters before the first insert. The obtained spectra are presented in Figs. 10, 11 and 12 for different glucose syrup solutions used for Reynolds number of 40, 640 and 2560, respectively.

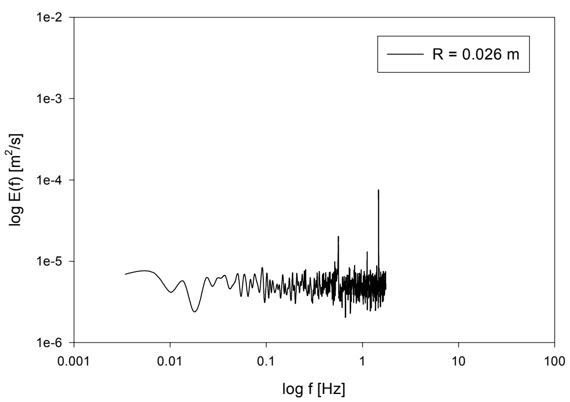


Fig. 10. One-dimensional fluctuation energy spectrum, Inlet, Re=40, R=0.026m

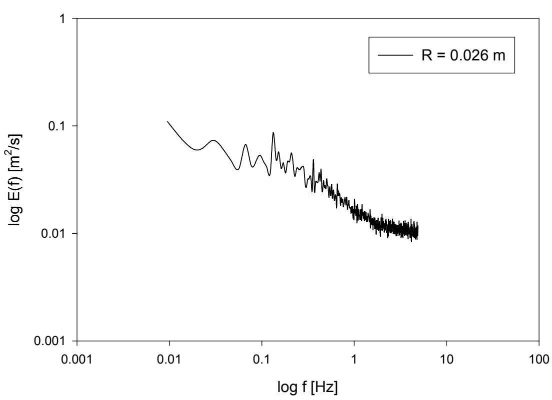


Fig. 11. One-dimensional fluctuation energy spectrum, Inlet, Re=640, R=0.026m

At Re=40 the fluctuation energy value was in the range from 10^{-6} to 10^{-4} m^2/s. Again at the frequency of about 1.5 Hz a peak appeared (Fig. 10), which suggests possibility of small fluctuations of the mean flow with that frequency. Significantly higher values of the energy density were found for Re=640, and ranged from 0.01 to 0.1 m^2/s (Fig. 11). The energy spectrum had a well-defined descending part at higher frequencies, which suggests that the turbulent flow was relatively well developed. Similar features showed the spectrum for Re=2560 (Fig. 12), however, the fluctuation energy density was slightly smaller – from about 0.01 to 0.07 m^2/s. Perhaps this was the reason why the spectrum did not descend as steeply as for Re=640.

The inlet plots for glucose syrups were compared with similar spectra obtained for a shear-thinning solution of carboxymethylcellulose (CMC) at Re=40 and 120, which were obtained experimentally also for validating other CFD numerical simulations. An example of such a plot is shown in Fig. 13 for Re=120. The basic features of the spectra for CMC were very similar to those for the glucose syrup reported in this paper for corresponding Re level. For instance, at Re=40 the characteristic peak at about 1.5 Hz appeared again.

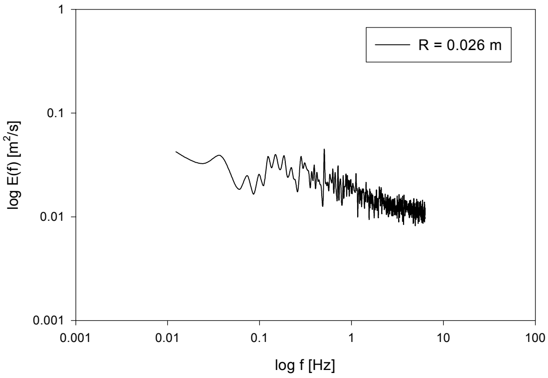


Fig. 12. One-dimensional fluctuation energy spectrum, Inlet, Re=2560, R=0.026m

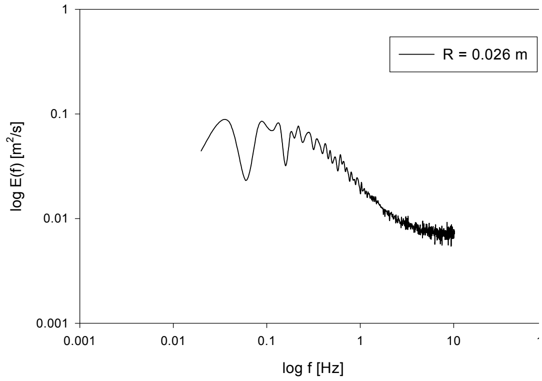


Fig. 13. One-dimensional fluctuation energy spectrum, Inlet, Re=120, CMC, R=0.026m

An interesting conclusion resulted from the analysis of the energy spectrum for CMC at Re=120. It showed typical features characteristic for the developed, turbulent flows at higher frequencies (Fig. 13). This suggests that already at that level of Reynolds number significant instabilities of the flow may be present and possibly transitional flow was developed. In order to clarify that question it was also decided that the future experimental programme for the Newtonian fluid flow should cover the range from Re=40 to 640.

CONCLUDING REMARKS

The performed analysis of the velocity fluctuation spectra led to the conclusion that they were almost identical for the L1 and L2 axial distances when keeping Re, α and R constant. This confirms that the flow characteristics in the fifth insert were symmetrical, irrespective of the flow intensity, radial and angular position of the measurement point.

Based on the presented results it may be concluded that the onset of the vortexing flow can be detected already at Re=40. At higher Reynolds numbers from 640 to 2560, instabilities characteristic for the transitional and turbulent flows were found. However, it is necessary to widen the experimental programme in order to find out details of the transition from stable flow with systematic fluctuations to randomly fluctuating flows inside the static mixer inserts.

A broad data bank for validating numerical simulations was established.

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