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# Experimental investigations of liquid flow in pipe with flat internal baffles

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Liquid flow in a tubular reactor with flat internal baffles of various widths was investigated. On the basis of the laser Doppler anemometry (LDA) measurements, the main flow parameters, i.e. the mean and fluctuating velocity components and turbulent kinetic energy (TKE) were determined. The investigations demonstrated that the insertion of baffles into a pipe and a change in their width caused a generation of liquid stream whirls, induced liquid recirculation loops and intensified the flow considerably. The results can be useful in describing turbulent flow in tubular reactors with baffles and in optimising their design.


**Keywords:** tubular reactor, liquid flow, flow velocity, LDA measurements, tube with baffles, turbulent kinetic energy (TKE)

## Introduction

Tubular flow reactors are a group of process apparatuses in common use in industrial practice. In units of this kind, fluids flow in a duct (circular or rectangular in cross-section) with internal baffles which differ in design. The purpose of the baffles is to intensify momentum, heat, and mass transfer processes, which proceed in a fluid flow. Flow intensification in a tube promoted by static baffles can be observed in many apparatuses, e.g. in static mixers, tubular reactors, shell-and-tube heat exchangers, bioreactors, solar collectors, etc.

The advantages of flow reactors, e.g. their relatively simple design, low investment and operating costs, continuity of performance, and a high degree of mixing at a short liquid hold-up time (Stręk, 1981; Zlokarnik, 2001; Paul et al., 2004; Murasiewicz & Jaworski, 2013), make them economically viable alternatives to conventional stirred tanks with turbine impellers (Szoplik & Karcz, 2005). Flow reactors can be used in various industrial technologies, especially when conventional stirred tanks are less economical, e.g. in high viscosity emulsions, suspensions (Grace, 1982; Furling et al., 2000), or as chemical reactors with simultaneous heat exchange (Craig, 1987). Tubular flow reactors are also used as bioreactors, especially for biological systems that degrade in time (Paul et al., 2004) and as photo-bioreactors for intensive microalgal production (Olivieri et al., 2014).

The problem of fluid flow in a duct with internal baffles continues to be the subject of many theoretical analyses and experimental investigations. These have sought to study the influence of baffle geometry and their location within a reactor on flow hydrodynamics and the course of a process. Al-Atabi et al. (2005a, 2005b) examined flow structure in a tubular reactor (Reynolds numbers of 50–5000) with a visualisation method based on fluorescent dye injection. They observed substantial flow intensification caused by baffles and a turbulent flow for a fluid with its Reynolds number as low as 250. They also studied the effect of baffles on flow resistance. It was demonstrated that the friction factor of the tube with baffles decreased with increasing Reynolds numbers but was always greater than that determined for a laminar

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flow in a tube without baffles. In a subsequent paper (Al-Atabi, 2011), the author analysed the effect of baffle height in a reactor on the degree of mixing brine with water. An increase in the mixing degree with the growth of baffle height was noted but it occurred at the expense of higher flow resistance and more energy expenditures. The author proposed that the increase in the mixing degree was due to baffle-generated intensive turbulent flow in the pipe and emphasised the importance of accurate measurement of turbulent flow parameters in the vicinity of baffles. Mehdi and Mushatet (2008) carried out numerical simulations of an air flow and heat exchange in a pipe with baffles. In simulations, they changed the height and thickness of baffles and the intervening distance. They also analysed the influence of baffle location in a pipe (inline or staggered arrangements) on a flow structure. In numerical calculations the $k$–$\varepsilon$ turbulence model was adopted. The flow velocity profiles so obtained illustrated the essential influence of baffle geometry on the gas recirculation zones they generated. However, it should be noted that the results were mainly presented in a qualitative way. The authors did not provide suitable quantitative relations and dependencies, in particular, the scaling of vectors, representing the flow velocity in a pipe. They concluded that the staggered arrangement of baffles presented higher values of a turbulent kinetic energy rather than the inline energy. Mendoza Marín et al. (2006), based on CFD simulations, analysed the effect of internal baffles that were inclined to the tube axis. They examined the efficiency and course of the emulsion homopolymerisation process of styrene under non-isothermal conditions. The results were compared against a reactor without any baffles. Their research confirmed the essential influence of baffles and an increase in process efficiency in respect of viscosity and average particle size.

It is recognised that tubular flow reactors with internal baffles are applied in the industry as bioreactors. Wang et al. (2014) examined the effect of both the presence and geometry of baffles on flow conditions (liquid flow velocity and turbulent kinetic energy) and the bioprocess capacity using CFD simulations. Investigations were performed for an aerated tubular bioreactor, rectangular in cross-section. On the basis of the predicted values and on their experimental verification, it was stated that optimal performance of the reactor occurred when the distance between adjacent baffles was equal to the duct width and the baffle height was 0.5 of the duct width. Under these conditions, a circular flow with uniform liquid velocities was observed. The flow was accompanied by intensive mixing with the highest turbulence kinetic energy values in the zones between the baffles. The authors concluded that this bioreactor arrangement was useful in intensifying the aeration process. Similar simulations were also conducted by Yang and Hwang (2003). They studied the air-flow in a duct which was rectangular in cross-section. Inside the duct, internal baffles were located. The Reynolds numbers of the flow were in the range of $1 \times 10^4$–$5 \times 10^4$. The authors analysed the distributions of stream-wise velocity for both solid-type and porous-type (with orifices) baffles. Simulations were performed for various baffle height and fixed distance values between them (equal to duct-width). The investigations showed that, in the case of solid-type baffles, an increase in their height induced an intensive fluid circulation in the zones between the baffles and much higher flow velocities close to a duct wall. This was associated with the heat exchange intensification in the flow and also with an increase in flow resistances. However, the authors did not present any information on the parameters of flow turbulence generated by baffles and the quantities determining heat exchange intensification. Heat transport intensification in a fluid flow around baffles that were located in a pipe was also the objective of research by Tandiroglu (2006, 2007). These experiments showed a correlation describing the influence of baffle height, intervening distance and baffle orientation on the transient forced convection. The ratios of both smooth to baffled sectional areas and tube length to baffle spacing were also investigated. The author proposed a relation for calculating of pressure drop in a pipe with baffles, valid in the range of $3000 \leq Re \leq 20000$.

Analysis of the current state of the discipline revealed most investigations concerning tubular reactors/pipes with internal baffles to be based on numerical simulations (usually CFD simulations) only. In some cases, CFD-predicted values were not experimentally validated or confirmed by adequate measurements.

The present study was focused mainly on laboratory experiments carried out in a real tubular reactor with different geometry and internal baffles. On the basis of the measurements conducted with a two-channel, laser anemometer (laser Doppler anemometry technique) some parameters, e.g. the mean values of flow velocity, velocity fluctuations, and the turbulent kinetic energy of flow were determined. The results can be useful in describing turbulent flow in tubular reactors with baffles and in optimising their design.

## Experimental

Measurements were conducted in a tubular reactor of $D = 0.036$ m in internal diameter, equipped with six alternately located flat vertical baffles (Fig. 1). The width of the baffles changed between $h = 1/3D$, $h = 1/2D$ and $h = 2/3D$. The thickness of the baffles did not vary: $b = 0.002$ m. The distance between the adjacent baffles $a$ was fixed and equal to the internal reactor diameter, i.e. $a = D$. Preliminary analyses of the flow in this reactor were conducted with the aid of

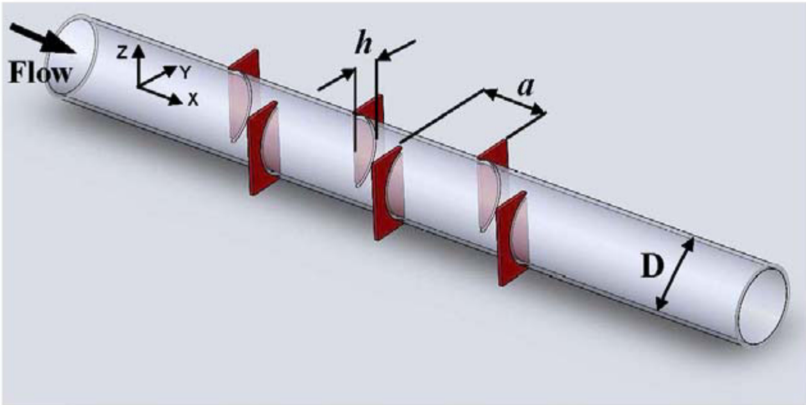


**Fig. 1.** Scheme of investigated tubular reactor with baffles.

CFD simulations and detailed previously (Wójtowicz & Talaga, 2014).

Experimental LDA measurements of instantaneous flow velocities were performed for selected measuring points (Fig. 2) located in cross-sections (planes) from x1 to x5 between adjacent baffles (1)–(6), and also for points located in the baffle planes. Additional measuring points were located in plane x6, situated at a distance equal to $2D$, beyond the last baffle.

The distribution of measuring points in each of the reactors ($h = 1/3D$, $h = 1/2D$, and $h = 2/3D$, respectively) is shown in Fig. 2.

A diagram of the experimental set-up is shown in Fig. 3. The experimental set-up consisted of three elements:

i) tubular reactor equipped with six flat internal baffles,

ii) supply system providing a continuous liquid flow in the pipe (including a flow-rate measuring system and control system),

iii) laser anemometer (LDA system) for measuring instantaneous flow velocities in the reactor.

The main element of the experimental set-up was a tubular reactor with flat internal baffles whose geometry is illustrated in Fig. 1. Its pipe and baffles were made of diaphanous organic glass. Distilled water was used as a working fluid. The use of distilled water during the experiments was dictated by the rigorous requirements of accurate measurements with the laser anemometer; the gas bubble deposition on a pipe wall was completely eliminated. To align the velocity profile and to provide a stable and undisturbed liquid inflow on the first baffle, the pipe length at the inlet was greater than $15D$, i.e. it was 0.6 m. The tubular reactor was encased in a cuboid jacket to minimise measuring errors resulting from laser light refraction during its transmission by a pipe wall. The cuboid jacket, similar to the reactor tested, was also made of diaphanous organic glass and filled with distilled water. At the jacket and at the inlet section of the pipe, two valves were mounted to de-aerate the reactor when it was filling with water. The pipe with baffles was an interchangeable element of the reactor, facilitating easy exchange of pipes with different geometry of baffles. Water flowing through the reactor was pumped in a closed system to maintain the same amount of tracer particles in the water, as required for laser measurements.

Measurements of liquid flow in the reactor were conducted using a two-channel, laser Doppler anemometer (the LDA technique), manufactured by Dantec (Dantec Dynamics A/S, Skovlunde, Denmark). The light beam generated by an argon-ion laser was split by a modular optical system into four independent measuring beams, i.e. two blue beams of 488 nm wavelength and two green beams of 514.5 nm wavelength. The LDA system was operated in the back scatter mode (Durst et al., 1987) with both transmitting and receiving optics in the same module as a measuring probe. The adjustment of a suitable measuring point in the reactor was obtained by appropriate probe- tracking. The probe was mounted on a triple-axis traversing system and numerically controlled by software. As seeding particles (flow tracers), silver-coated hollow glass spheres of 10 μm in diameter were used. The tracer concentration in the flowing liquid was determined experimentally to obtain a suitable data rate. The data acquisition and processing were conducted using a Dantec Burst Spectrum Analyser (the BSA processor). The total number of individual velocity measurements was 10 k points per measurement position and the data rate was up to 1 kHz. The measuring data acquisition was controlled by a computer and the BSA flow software (Dantec Dynamics, 2005).

Measurements of the instantaneous flow velocities in the reactor were conducted for the steady-state conditions of water flow in a tube ($Re = 5000$ determined in a pipe zone at the reactor inlet). This resulted in a turbulent flow regime being obtained in the baffle region (Al-Atabi et al., 2005a, 2005b; Al-Atabi, 2011). The accuracy of the Reynolds number determination for the flow in a pipe was $Re = 5000 \pm 79$, which corresponded to the mean velocity of flow in the in-

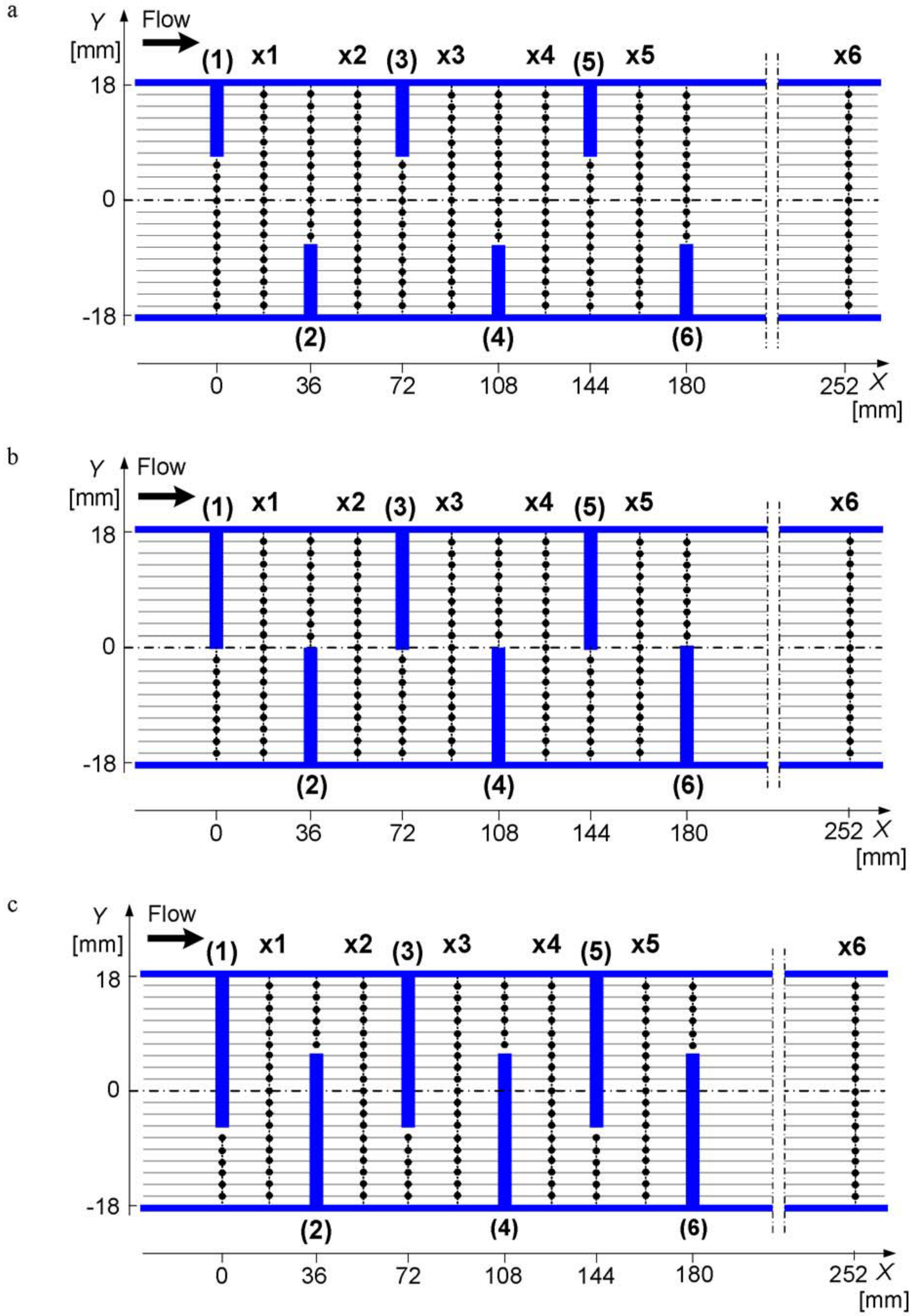


**Fig. 2.** Location of measuring points in tubular reactors with baffles of width: $h = 1/3D$ (a), $h = 1/2D$ (b), $h = 2/3D$ (c).

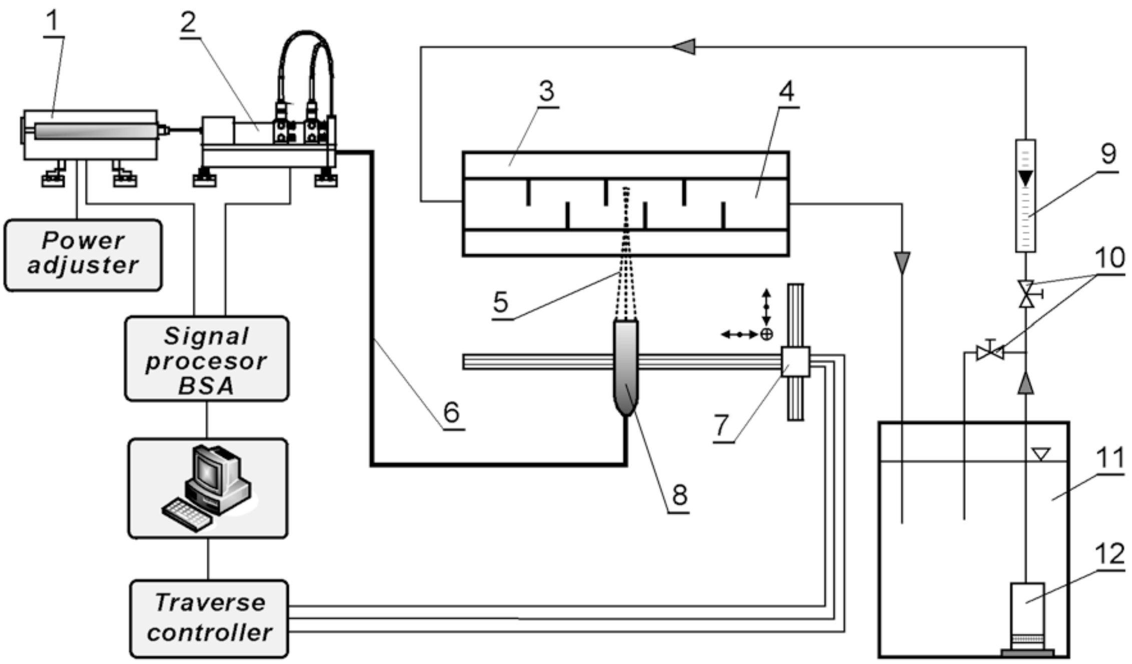


**Fig. 3.** Diagram of experimental set-up: 1 – Ar-ion laser, 2 – optical system, 3 – reactor housing, 4 – pipe with baffles, 5 – laser beams, 6 – multimode fibre, 7 – traverse 3-D, 8 – measuring probe, 9 – rotameter, 10 – control valves, 11 – liquid reservoir with tracer particles, 12 – submersible pump.

let pipe (before baffles) equal to $u = (0.139 \pm 0.002)$ m s$^{-1}$. The relative measurement uncertainty of the velocity determined for the corresponding parameters of the LDA-system and the measuring conditions was $\pm$ 3.28 %.

## Results and discussion

After setting the flow-rate and total de-aeration of the tube, measurements of instantaneous flow velocities were conducted for successive measuring points. A coincident measurement of two velocity components lying in two perpendicular directions was carried out, i.e. the axial $u_x$ (towards the main liquid flow along the pipe axis) and the radial velocity $u_z$ (along baffle width) (Fig. 1).

Based on results of LDA measurements consisting of a time series of instantaneous velocity measurements $u_i$, mean velocities of flow $\bar{u}_i$ for each $i$-component of velocity were determined using the following equation:

$$\bar{u}_i = \frac{\sum_{j=1}^{N} u_{i,j} w_{i,j}}{\sum_{j=1}^{N} w_{i,j}} \tag{1}$$

The fluctuating components of velocity (rms velocity) $u'_i$, were calculated as follows:

$$u'_i = \sqrt{\sigma_i^2}\ s = \sqrt{\overline{u}_i'^2} \tag{2}$$

where:

$$\sigma_i^2 = \overline{u}_i'^2 = \frac{\sum_{j=1}^{N} (u_{i,j} - \bar{u}_i)^2 w_{i,j}}{\sum_{j=1}^{N} w_{i,j}} \tag{3}$$

The quantity $w_i$ in Eqs. (1) and (3) is the weighing factor and $N$ represents the number of measurements of instantaneous velocities for a given measuring point. The weighing factor $w_i$ for $i$-component of velocity characterises the correction of the so-called sampling bias, which is entailed in all LDA measurements. This results from a non-homogeneous concentration of seeding particles (Albrecht et al., 2003). Several error correction methods have been proposed (DeGraaff & Eaton, 2001; Zhang, 2002). A method was selected based on the calculation of velocities as weighted averages with the weights corresponding to the residence time $\tau_{\rm res}$ of seeding particles in a measuring space, the so-called residence time weighting (Venneker et al., 2010). Hence, in Eqs. (1) and (3), it finally was assumed that $w_i = \tau_{{\rm res},i}$.

The measure of turbulence intensity is the turbulent kinetic energy $k$ (TKE). This quantity is described by the following overall equation:

$$k = \frac{1}{2}\left(\overline{u}_x'^2 + \overline{u}_y'^2 + \overline{u}_z'^2\right) \tag{4}$$

When two components of fluctuating velocities ($u'_x$ and $u'_z$) are measured, the magnitude of turbulent kinetic energy can be calculated (Zakrzewska, 2003; Za-

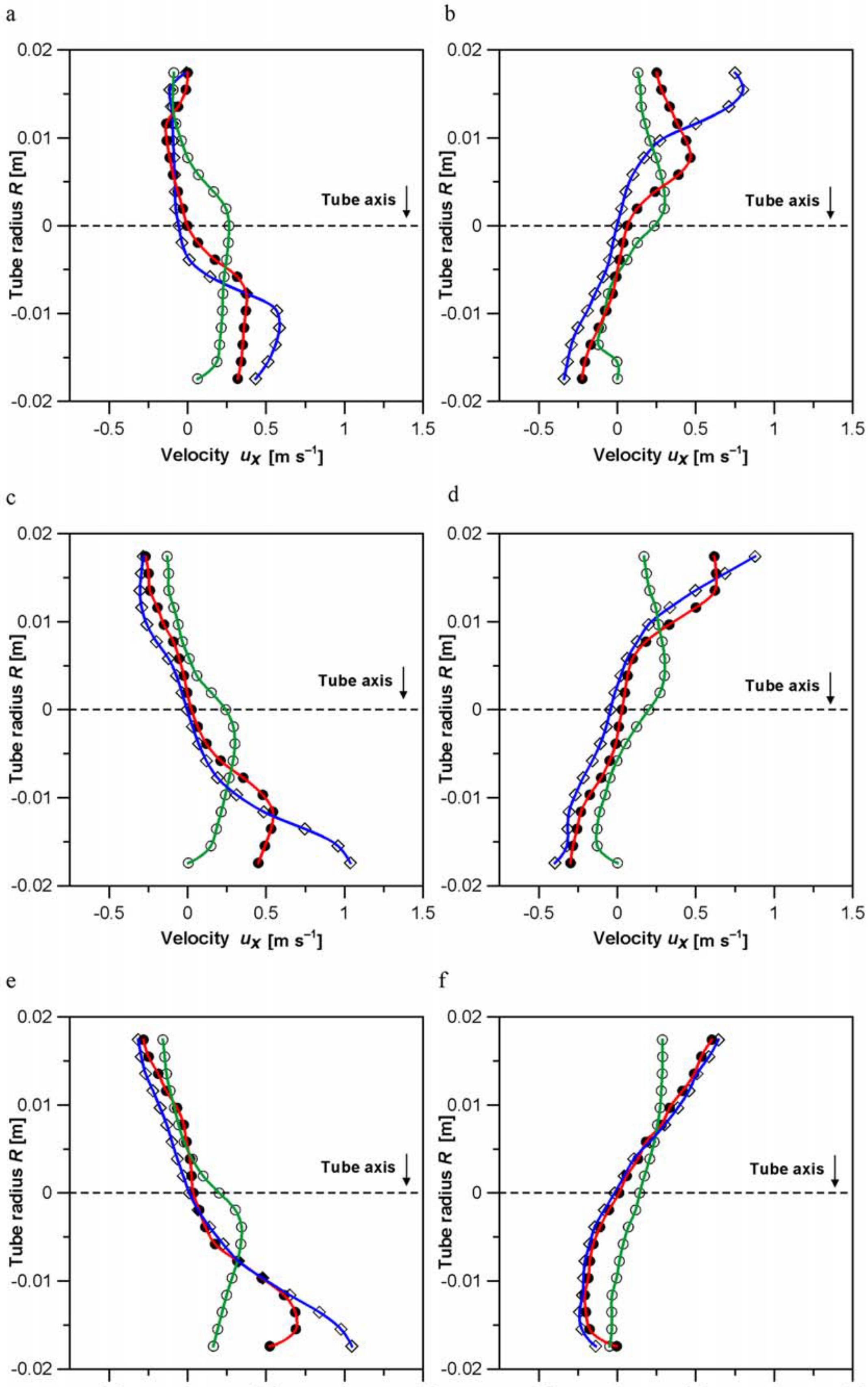


**Fig. 4.** Changes to axial $u_x$ component of mean flow velocity in x1–x6 cross-sections (a)–(f), respectively, and various baffle widths: $h = 1/3D$ (○), $h = 1/2D$ (●), $h = 2/3D$ (◇).

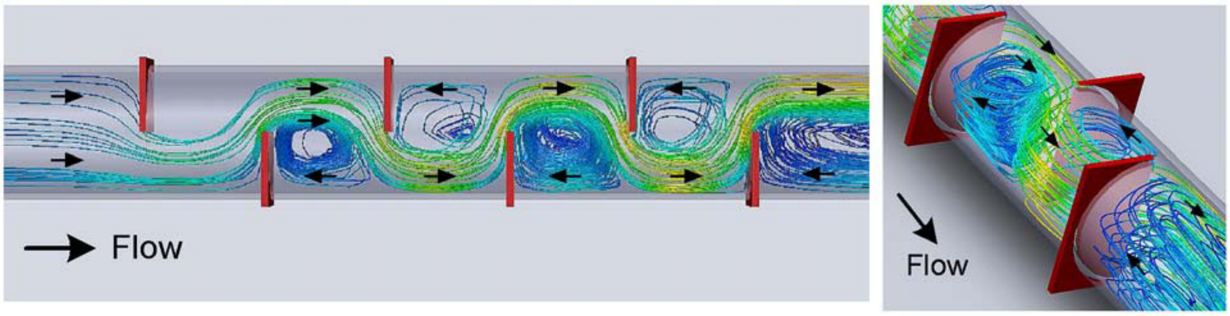


**Fig. 5.** Reference visualisations of streamlines for liquid flow in pipe with baffles ($h = 1/2D$) (SolidWorks FS).

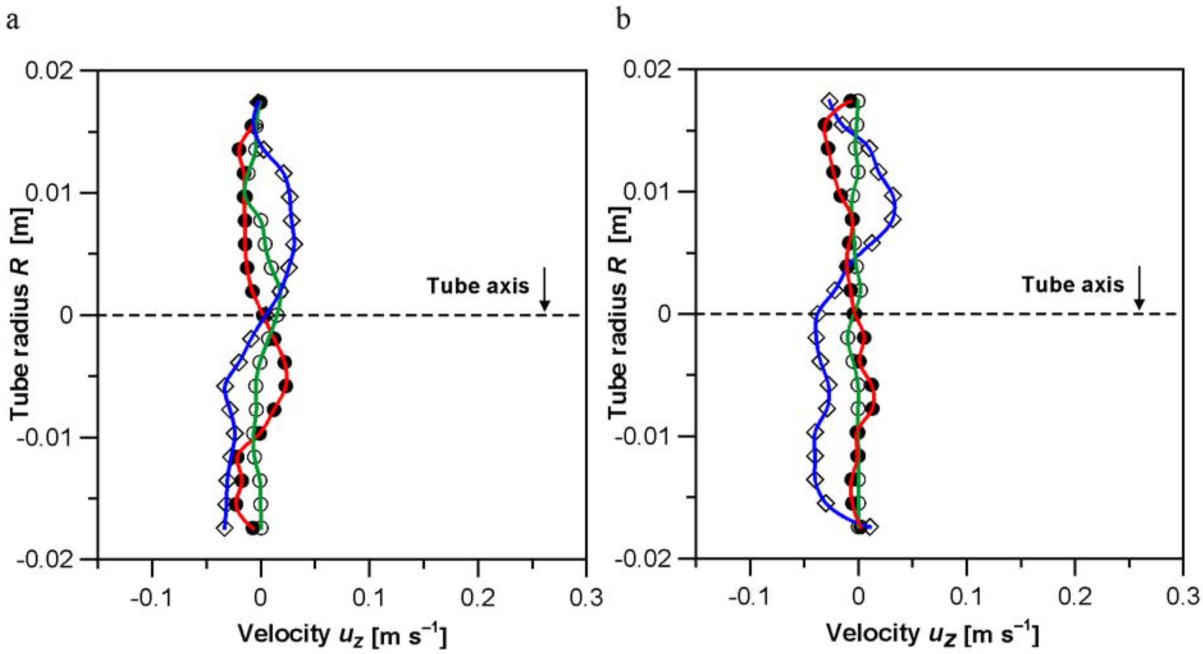


**Fig. 6.** Changes to radial $u_z$ component of mean flow velocity in x3 (a) and x4 (b) cross-sections and baffles of various widths: $h = 1/3D$ (○), $h = 1/2D$ (●), $h = 2/3D$ (◇).

krzewska & Jaworski, 2004) from:

$$k = \frac{3}{4}\left(\overline{u}_x'^2 + \overline{u}_z'^2\right) \tag{5}$$

The diagrams in Fig. 4 illustrate the mean velocity $u_x$ component distribution, i.e. velocity along the tube axis. These graphs show the distribution of velocities between successive baffles, i.e. for cross-sections x1, x2, x3, x4, x5 and additionally for cross-section x6, which was located at a distance of $2D$ beyond the last baffle (Fig. 2). The curves represent the results obtained in all three reactors with baffle widths: $h = 1/3D$, $h = 1/2D$ and $h = 2/3D$, respectively. Fig. 5 shows reference visualisations of streamlines (SolidWorks FS) obtained for a baffle width of $h = 1/2D$. Analysis demonstrated that insertion of baffles inside the pipe causes the generation of liquid recirculation loops in the zones behind the baffles. In this region, the liquid flows to a baffle and the axial components $u_x$ of a mean flow velocity are negative (Fig. 4), whereas velocities $u_x$ in front of the baffles have positive values; their sense is consistent with the direction of liquid flow in the pipe. In the zones behind the baffles, it is possible to see not only a change in $u_x$ component sense but also an absolute velocity decrease. The highest $u_x$ velocities were observed for the widest baffles (close to tube wall) and their values are approximately 4–5 times higher than those for the narrowest baffles (Figs. 4c and 4e). This can be explained by an increase in flow resistance with an increase in baffle width (Yang & Hwang, 2003; Al-Atabi, 2011). The previously described recirculation zones behind the baffles are also seen beyond the last baffle when the liquid flows through the hollow section of the pipe. At the distance of $2D$ beyond the last baffle, the $u_x$ velocity profile is still characterised by negative values in the region beyond the baffle and positive ones in the remaining zone (Fig. 4, cross-section x6),

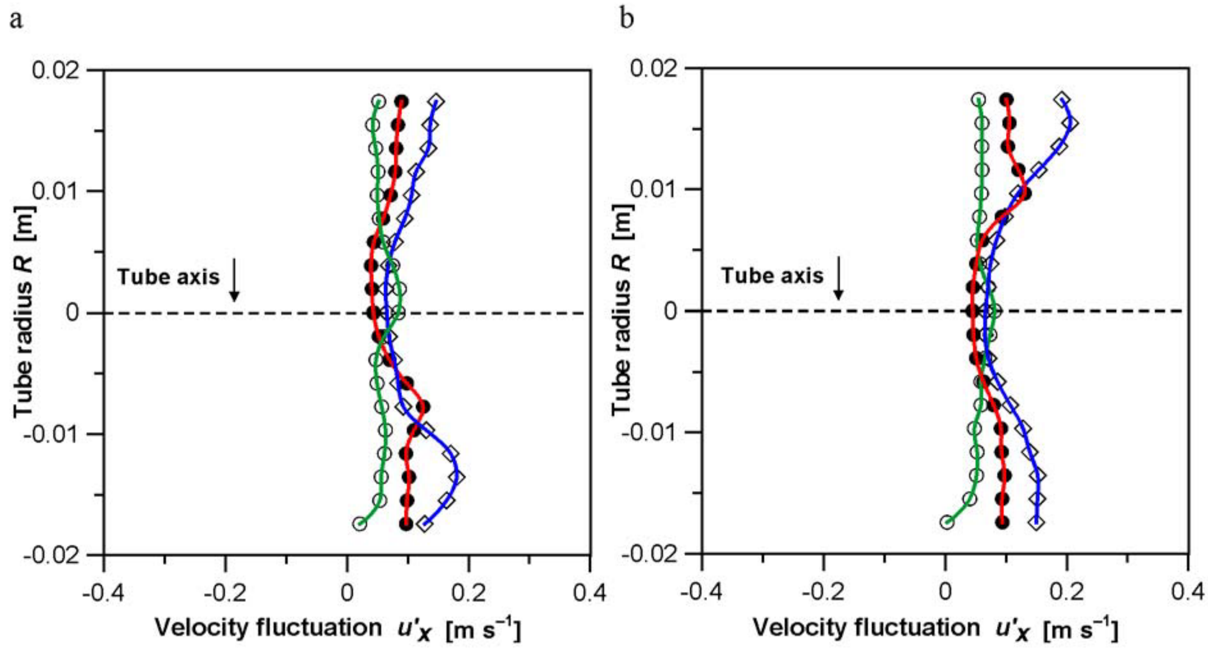


**Fig. 7.** Results of LDA measurements of fluctuating velocity component $u'_x$ in x3 (a) and x4 (b) cross-sections and various width of baffles: $h = 1/3D$ (○), $h = 1/2D$ (●), $h = 2/3D$ (◇).

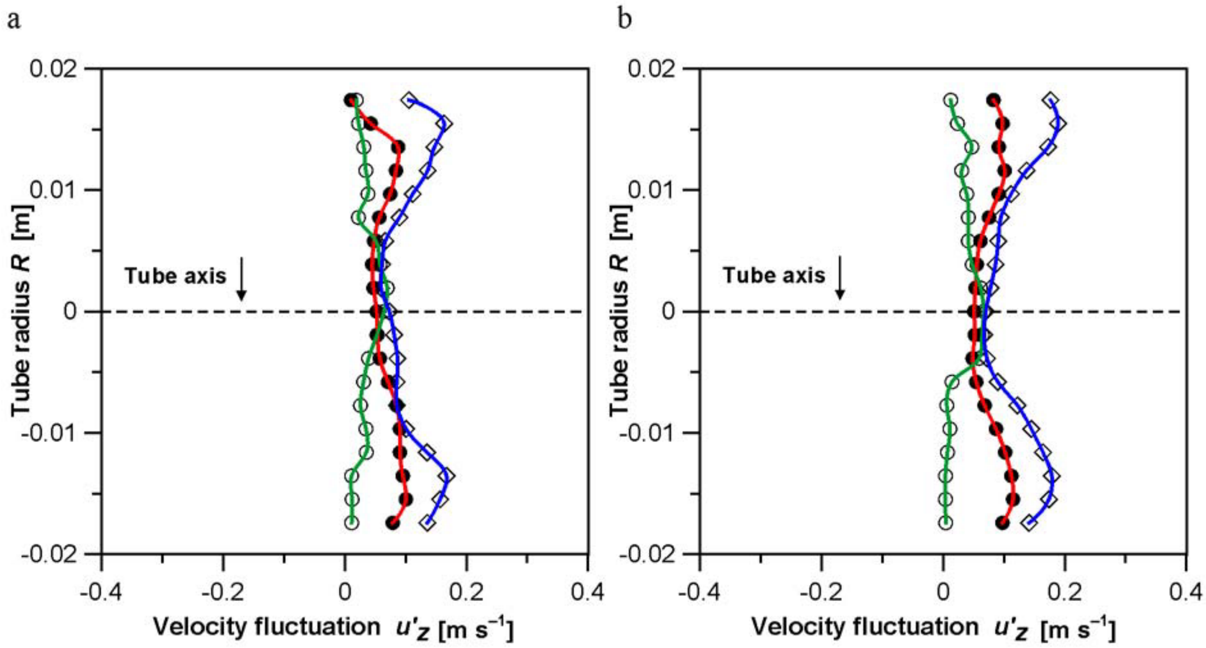


**Fig. 8.** Results of LDA measurements of fluctuating velocity component $u'_z$ in x3 and x4 cross-sections and various width of baffles: $h = 1/3D$ (○), $h = 1/2D$ (●), $h = 2/3D$ (◇).

where, in the case of the smallest width baffle ($h = 1/3D$), the velocity profile was most aligned along the pipe diameter. This indicates the smallest flow disturbance in the pipe with the narrowest baffles.

Fig. 6 shows changes to the radial velocity component $u_z$. The measurements were made for cross-sections x3 and x4 behind two successive baffles (3) and (4), respectively. In this case as well as for all the other cross-sections, the profiles obtained were similar. It may be concluded that the number of baffles does not significantly affect the radial component of velocity. An interesting conclusion follows from a comparison of the axial velocity $u_x$ (Fig. 4) and the radial velocity $u_z$ (Fig. 6). The graphs show significantly lower values for radial components, wherein the highest differences obtained from analysis of all measurements

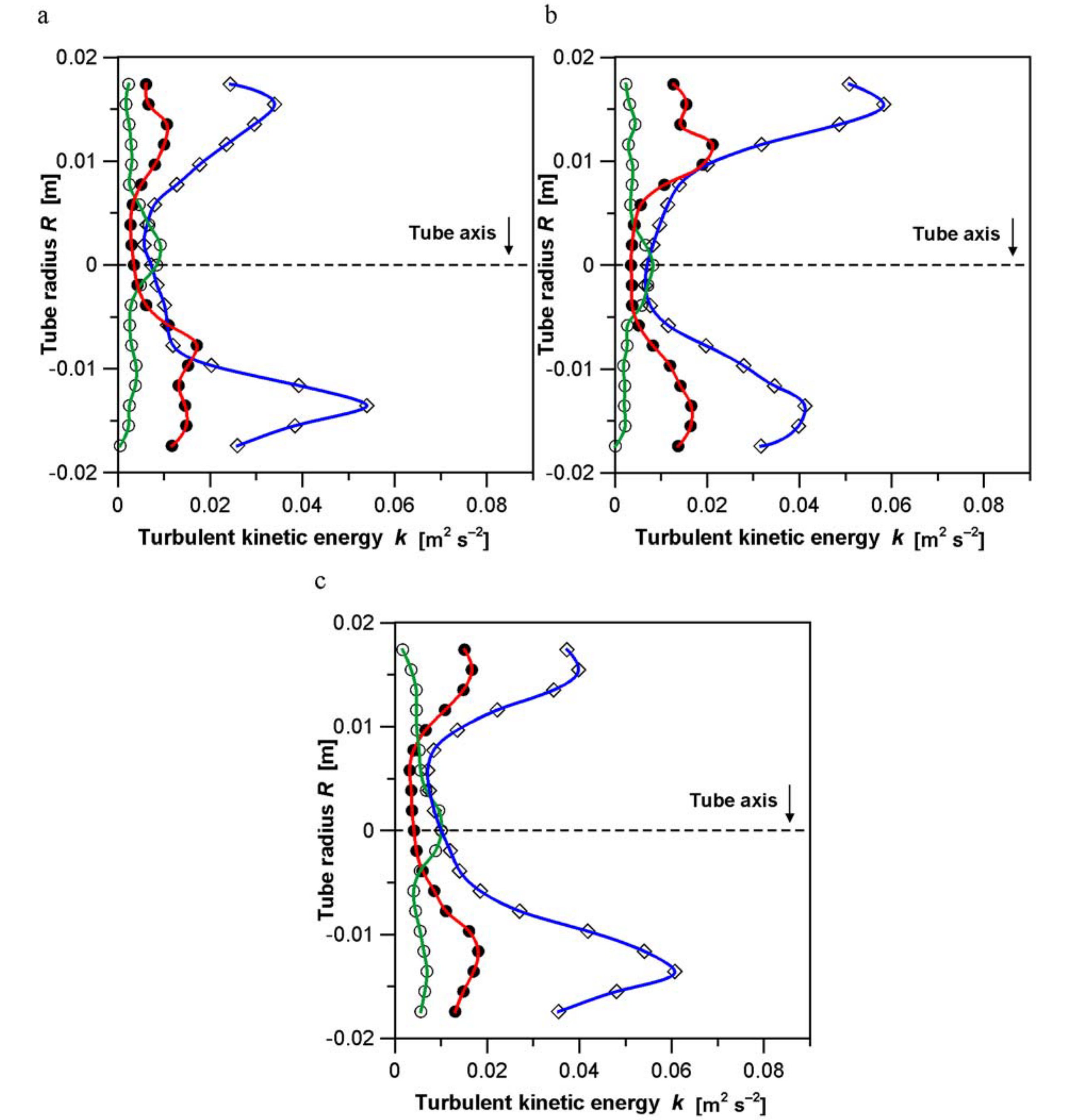


**Fig. 9.** Turbulent kinetic energy $k$ obtained in x3 (a), x4 (b) and x5 (c) cross-sections of pipes with baffles of various widths: $h = 1/3D$ (○), $h = 1/2D$ (●), $h = 2/3D$ (◇).

were in the order of 25 times.

Example measurements of fluctuating velocities are presented in Figs. 7 and 8. Fig. 7 shows changes to the axial $u'_x$ component of fluctuating velocity, while Fig. 8 presents the profiles of the radial $u'_z$ component.

Analysis shows that, with an increase in baffle width, velocity fluctuations also increase, and the growth is greater when the distance from the pipe axis increases. This testifies to the increase in flow turbulence caused by the baffle insertion inside the tube. Wider baffles induce more flow turbulence than do narrower baffles. This is also confirmed by the calculated values of the turbulent kinetic energy shown in Fig. 9. The highest values of TKE were observed in the zones beyond the baffles, while the lowest values were measured close to the tube axis. The widest baffles generate the highest values of the turbulent kinetic energy in the flow. For baffles of $h = 2/3D$, the maximal values of TKE are approximately 17 times greater than for the narrowest baffles of $h = 1/3D$. Calculations of the turbulent kinetic energy in planes x4 and x5, (in zones beyond baffles (4) and (5), respectively)

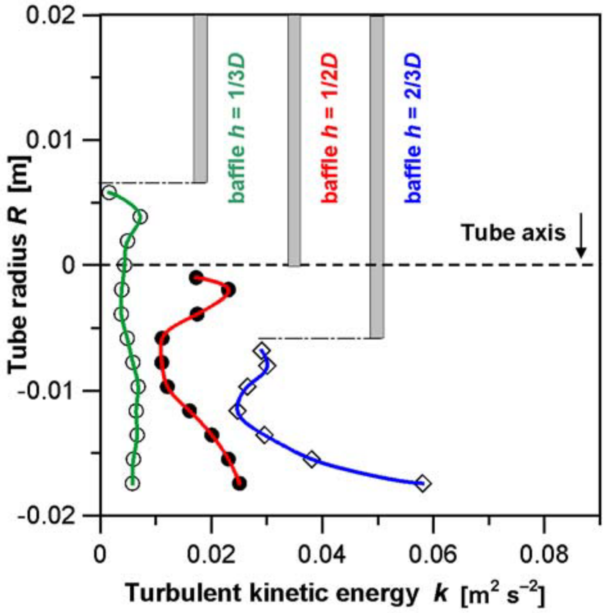


**Fig. 10.** Turbulent kinetic energy $k$ in plane of fifth (5) baffle and various width of baffles: $h = 1/3D$ (○), $h = 1/2D$ (●), $h = 2/3D$ (◇).

showed similar distributions and comparable values of the TKE for both cases. This means that, from the fourth (4) baffle, steady conditions of the turbulent flow pertain and the subsequent baffles do not cause any significant changes in the turbulent kinetic energy values.

Fig. 10 shows the values of turbulent kinetic energy obtained from the LDA measurements conducted in the fifth (5) baffle plane (Fig. 2) and various baffle widths. For the flow in this region, the maximum values of TKE were determined close to the pipe wall and they decreased in the vicinity of the baffle. Close to the baffle a local increase in the TKE can be seen. The widest baffles generate a flow with the highest turbulent kinetic energy in comparison with the flow in the pipe where the baffles had a smaller width. In this first case, the maximum values of TKE determined close to the pipe wall were approximately 2 times or even 7 times greater than those calculated for $h = 1/2D$ and $h = 1/3D$ baffles.

The maximal values of TKE determined near the pipe wall are 0.06 $m^2\ s^{-2}$ and these are higher than those obtained by Mehdi and Mushatet (2008), where the maximal values of TKE were 0.05 $m^2\ s^{-2}$. The values of TKE determined close to the tube axis were 2 to 4 times smaller than the results presented in Mehdi and Mushatet (2008). The differences can be caused by the different baffle thickness or different values of the $Re$ number (present study $Re = 5000$, $Re = 6100$ (Mehdi & Mushatet, 2008)).

## Conclusions

In this study, measurements of mean flow velocities and fluctuating velocity components for a turbulent liquid flow in a pipe with flat, internal baffles of various widths are presented. The measurements were conducted using the laser-Doppler anemometry (LDA) technique. From the results obtained, the values of turbulent kinetic energy (TKE) in the flow were determined.

The investigations demonstrated that a baffle insertion into a pipe caused the generation of liquid stream whirls and induced liquid recirculation loops. The mean velocities $\bar{u}_x$ in front of the baffles are always positive, i.e. their sense is consistent with the main direction of liquid flow in a pipe. In the zones with liquid recirculation behind the baffles, the reverse is true and a change in $\bar{u}_x$ sense can be observed (it has an opposite direction to the main liquid flow) as well as a decrease in absolute velocity values in comparison with the velocities measured in front of a baffle. For the widest baffles ($h = 2/3D$), the axial velocities $u_x$ of liquid inflow on a baffle are around 3 to 8 times greater than those for the narrowest baffles, but the velocity drop behind the widest baffles is the highest. These results confirm the conclusions presented by other authors that flow resistances increase when baffle width is increased.

Baffle width also affects the magnitude of the fluctuating flow velocities. Measurements of this parameter showed that, when baffle width was increased, the axial $u'_x$ and radial $u'_z$ fluctuating velocities increased and this growth was greater when the distance from the tube axis increased. Accordingly, the insertion of baffles inside a tubular reactor induced an essential flow turbulence increase. This tendency was also confirmed by the turbulent kinetic energy calculations. In the pipe with the widest baffles ($h = 2/3D$), the turbulent liquid flow was characterised by the highest values of TKE. In the case of the reactor equipped with the widest baffles, the maximal values of turbulent kinetic energy were around 17 times greater than for the reactor with the narrowest baffles. It was also found that the TKE had fixed values after the fourth baffle.

## Symbols

| | | |
|---|---|---|
| $a$ | distance between adjacent baffles | m |
| $D$ | tube diameter | m |
| $h$ | baffle width | m |
| $k$ | turbulent kinetic energy (TKE) | $m^2\ s^{-2}$ |
| $N$ | number of data collected for each measurement point | |
| $R$ | tube radius | m |
| $Re$ | Reynolds number for empty pipe | |

| | | |
|---|---|---|
| $u_i$ | instantaneous velocity component in $i$-th direction | m s$^{-1}$ |
| $\bar{u}_x$ | axial component of mean velocity | m s$^{-1}$ |
| $\bar{u}_z$ | radial component of mean velocity | m s$^{-1}$ |
| $u'_x$ | fluctuation velocity in axial direction | m s$^{-1}$ |
| $u'_z$ | fluctuation velocity in radial direction | m s$^{-1}$ |
| $w_i$ | weighing factor for $i$-th component of velocity | s |
| $\sigma$ | standard deviation | m s$^{-1}$ |
| $\tau_{\text{res}}$ | residence time of seeding particles at measurement point | s |

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