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Characterization of viscosity dependent residence time distribution in the static micromixer Statmix6

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ABSTRACT

The residence time characteristic of the static micromixer Statmix6 (IPHT Jena) was determined by a pulse trace experiment applying a microphotometric measurement set-up with two flow-through detectors. The residence time distribution (RTD) shows a characteristic shift with viscosity and flow rate. The change in RTD cannot be described by reconsidering the Reynolds number exclusively. A RTD tailing factor Θ_{99} was introduced for the quantitative description of parameter effects on the RTD. The tailing factor Θ_{99} is defined as the dimensionless time which is needed for the residence time sum function $F(\Theta)$ to reach a value of 99%. The tailing factor comprises only the elimination kinetic of the RTD without respect to the skewness. At lower flow rates, the change of the RTD tailing factor with flow rate is nearly independent on viscosity. In a transition region, the RTD tailing factor is strongly reduced, but the characteristic Re number of transition depends on viscosity. This RTD tailing factor characteristics was compared with the RTD characteristic of a straight PTFE tube (1 mm inner diameter) and a commercial interdigital micromixer (Mikroglas, Mainz) under equal conditions and comparable mean residence times (about 0.5–40 s). In the tube, a reduction of the tailing factor with increasing flow rate was observed too. But, the change of the RTD tailing factor characteristic of the tube differs considerably from the flow rate and viscosity dependence characteristic found in the static micromixer. The experimental results were interpreted by changes in the flow regime under different convection mechanism inside the microdevices. Changes in mechanism exist in case of the complex fluidic geometry of micromixers as well as in case of the simple tubes. But, the characteristic transition regions for the RTD tailing factor are strongly influenced by the structure of device and by the viscosity of the liquid feed.

1. Introduction

The realization of fast mass and heat transfer is one of the most important reasons for the application of microreactors beside the general reduction of process volumes. Fast mixing and fast heat exchange are required to intensify processes and for new process windows in order to enhance the efficiency and the yield of continuous flow synthesis [1,2]. The need for short times constants of heat transfer and short time constants for mixing is always connected with the existing flow regime. Under microfluidic conditions, this aspect is of particular importance due to the predominant laminar flow regime. The absence of turbulences and the prevailing of laminar flow regimes are caused by the low Reynolds numbers which are typical for the applications in microchannels and microreactors. The laminar flow results in large fluidic dispersion and is the reason for broad residence time distributions. The fluidic dispersion stands in contradiction to the desired time constants for fast mass and heat transfer. Therefore, the optimization of the residence time characteristics is a key issue in microreaction technology.

The determination of the residence time characteristic is one of the most important aspects for the optimization of microreactors and whole microreaction arrangements. In contrast to conventional reactors, neither the classical models for continuously stirred tank reactors nor the dispersion model for pipes are applicable easily. Homogenous flowing fluids in microtubes or channels with constant cross-section stay mostly in the laminar flow regime with more or less distinctively developed secondary flow effects. Secondary flow effects obviously cause flow rate dependent changes in the residence time distribution and changing dispersion in microfluidic systems [3]. Here, the RTD tailing factor (Eq. (1)) can help to study flow rate and viscosity dependent effects with just

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one simple parameter. The tailing factor Θ_{99} describes the dimensionless time needed to reach 99% of the RTD integral.

$$F(\Theta) = \int_0^{\Theta_{99}} E(\Theta)d = 0.99 \quad (1)$$

The residence time characteristic in micromixers becomes still complex due to complex channel geometries and resulting flow regimes. The superposition of convection effects on the one hand with different conditions for diffusion due to different thicknesses of lamella structures on the other hand leads to complex trajectories of molecules inside the micromixers. The local flow regimes take strong influence on the RTD and cause the device characteristics. Here, complex secondary flow effects as well as ideal Poiseuille flow conditions may coexist. On the other hand parasitic volumes (dead volumes) can even increase the internal storage capacity for substances and the diffusive transport may cause broad RTD.

A theoretical prediction of the residence time distribution is complicate due to complex geometries and their effects on the fluid transport. Beside the reactor geometry, the complex dynamic of fluidic interfaces of different fluids play a key role for the RTD. In curved channels of defined geometry, the Dean number can be used to describe the flow regimes with centrifugal lamellae folding [4]. In complex microreactors with various curved geometries the application of the Dean number is difficult. Nevertheless, the theoretical basics for the description of fluid transport and diffusion is given by the Navier–Stokes equations and the Fick's Laws. An analytical description is difficult due to the complex geometrical problems. Therefore, FEM simulations for CFD or semi-empirical approximations must be applied for the description of residence time distributions under microfluidic conditions [5,6]. Such methods have to be used in all cases of complex geometries especially for micromixers. Branched microchannels represent a particular complex case of microfluidic geometry. Details about the residence time theory can be found in different textbooks [7–9]. The residence time characteristics of static micromixers using a multi-lamination strategy–interdigital structures or split and recombine structures can obviously not be approximated by the behaviour of a plain microchannel with comparable volume. Beside simulations, the experimental determination of the residence time characteristic is very important for the characterization and understanding of the influence of flow phenomena on the reaction performance [10]. Finally, the RTD characteristic determines the quality for the produced material.

The flow rate dependent RTD of the static micromixer Statmix6 (IPHT Jena) was investigated and compared with the RTD of a static micromixer made by Mikroglas (Mainz) [11] and with the RTD of a simple PTFE tube. The Statmix6 device consists on a series of split and recombine units and possesses an internal volume of about 8 μL [12]. The construction follows the principle of Si/glass/Si mixers as described by Schwesinger et al. [13], but the device was realized as a glass/Si/glass sandwich construction. The junctions for splitting and recombining the fluid streams are oriented in lateral and perpendicular direction alternatively in order to ensure optimal conditions for multi-lamination. The characteristic channel width of the Statmix6 is about 300 μm. The residence time behaviour of such type of micromixers is of particular interest in case of the consecutive application of two and three step static micromixers working with the same principle. In these devices, liquid feeds from three or four sources are mixed consecutively in a "2 + 1", in a "2 + 1 + 1" or in a "2 + 2" order. Each mixing step implements a series of 4–6 split and recombine units and the liquids are guided immediately from the split junction of the next recombining unit. Short mean residence times can take place due to very low internal volumes of the mixing units and due to avoiding parasitic channel volumes between the mixing units. Very short time intervals between the mixing steps can be realized if higher flow rates are applied. This is of importance for the product formation in fast two or three step chemical reactions, for example in the formation of colloidal solutions of binary or surface-functionalized metal nanoparticles [14,15].

It was expected, that the residence times characteristic of the micromixers is not only dependent on the flow rate but additionally influenced by the viscosity of the streaming liquid. Therefore, the flow rate effects on the RTD and the RTD tailing factors were investigated with a series of liquids with different viscosities. To adjust fluids with different viscosities water was mixed with different amounts of glycerol. Measurements were done in a tempered room of about: 25 °C. Following viscosities were used: mixtures of water with glycerol (% wt./wt.): 0% glycerol, η = 0.9 mP/s, 10% glycerol, η = 1.2 mP/s, 20% glycerol, η = 1.5 mP/s, 30% glycerol, η = 2.2 mP/s, 40% glycerol, η = 3.5 mP/s, 50% glycerol, η = 5.9 mP/s. For the calculation of the fluid density following linear equation was used: $\rho(25\,^{\circ}\mathrm{C}) = 1.0 \times 0.026 \times$ wt.% glycerol.

2. Experimental

2.1. Micromixers and experimental arrangement

The two investigated micromixers differ by the internal constructions and volumes. The internal volume of the mikroglas mixer is about 15 μL (including fluid ports) and is about two times larger than the internal volume of the Statmix6 device. The mikroglas mixer uses the multi-lamination principle by subdividing the inlet feeds in a series of 15 small lamellae. Small lamellae of the feed liquids were achieved in the Statmix6 device too. Here, a cascade of eight split and recombine units force the multi-lamination. Details about the construction of the devices were described earlier [11,12]. The measurement arrangement consists of a high quality syringe pump (NeMeSys, Cetoni GmbH, Korbußen, Germany) for the rate-controlled fluid actuation, an injection valve with internal sample loop of 1 μL volume and two microflow-through photometers arranged before and after the micromixer (Fig. 1). Both photometers are used for the determination of the tracer profiles before and after the micromixers. The arrangement allows a flow rate variation in a wide range. Flow rates between 50 and 3000 μL/min were applied in the experiments reported here. This flow rates correspond to mean flow velocities between about 1 and 64 mm/s in a channel of an internal diameter of about 1 mm. RTDs for all flow rates and viscosities were calculated using two different models: the dispersion model as described in [7,6] as well as a empiric model as described in the following chapter. The mean residence time was in the range of 0.75–50 s. An aqueous solution of Cochenille red A (about 10 mg/mL, E 124, absorbance 2.5 at an optical path length of 1 mm) was used for tracing. To guarantee identical viscosities in the feed fluid as well as the tracer the dye solutions were prepared from the investigated viscose fluid.

The parasitic volumes of connecting pipes between the photometers and the mixer were about 6 μL. However, this volume cannot be neglected compared to the inner mixer volumes. But, there was not a significant influence on the RTD observed. The observed residence time characteristic was clearly dominated by the mixers itself.

2.2. Microphotometric flow-through measurements and signal processing

The both microflow-through photometers are identically in construction. They consist on a LED (505 nm, 21 cd, Agilant), and a photodiode (Typ SFH 206K, Siemens) detection unit with appropriate electrical interconnectors. A transparent FEP-tube was fixed inside a drill hole in the centre of the device. The light path between

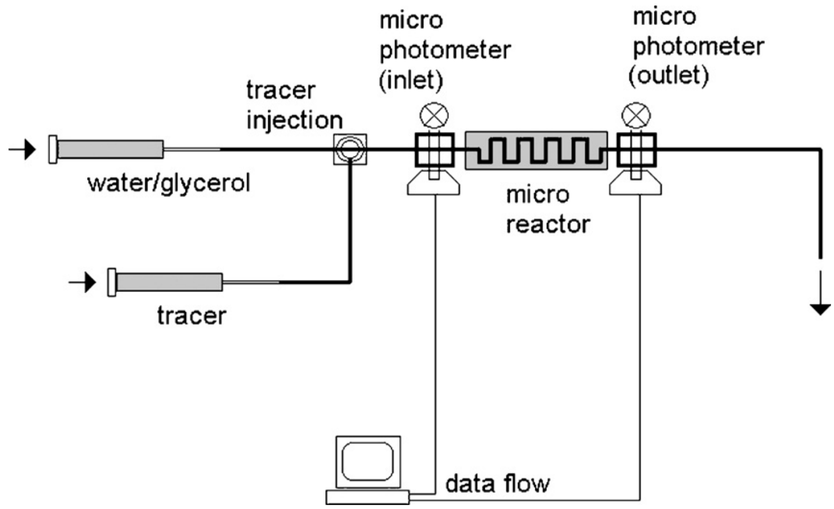

Fig. 1. Experimental set-up for optical residence time characterization with two micro flow-through photometers.

the exciting LED and the photodiode detector was about 3 mm only including a 300 μm aperture between LED and tubing. This short diameter ensures that the light is efficiently conducted through the liquid channel and the disturbance of light from the environment was minimized. The photometer device can be adapted to 1/16 tubes and adjusted as close as possible to the micromixer in- and outlets. The photometer devices were additionally protected against environment light disturbance by housing. The devices can be operated with a minimal time constant of about 0.2 ms. In this way absorbance data can be recorded with frequencies up to 5 kHz. This high resolution in time allows the exact measurement of tracer profiles even at high flow rates.

3. Results and discussions

Recent work addresses the influence of viscosity and flow rate on the residence time distribution of split and recombine mixers. Therefore, the before mentioned water/glycerol mixtures (up to 50 wt.%) were studied in the flow rate range between 50 and 3000 μL/min. A pressure loss up to 3 bars was observed in case of the high viscose fluids (50% glycerol) and high flow rates (3000 μL/min). The arising dissipated energy up to 5000 W/kg is typical for micromixers. But, a dissipative heating of the fluids can be neglected.

The RTD was calculated by analyzing the change of the tracer profile between the inlet and the outlet photometer. Therefore, the recorded inlet and outlet traces concentration $c(t)$ of the pulse have to be normalized. $C_{out}(t)$ and $C_{in}(t)$ are the normalized tracer signals and can be calculated from the recorded pulse traces using Eq. (2).

$$C_{in,out}(t) = \frac{c(t)}{\int c(t) \cdot dt} \tag{2}$$

$$C_{out}(t) = C_{in}(t) * E(t) = \int_0^t C_{in}(t') \cdot E(t - t') \cdot dt' \tag{3}$$

$$C_{out}^{calc}(t) = C_{in}(t) * E(t) \tag{4}$$

$$\varepsilon = \sum [C_{out}(t) - C_{in}(t) * E(t)]^2 \cdot \Delta t^2 \Rightarrow \min \tag{5}$$

$$E(t) = A \cdot e^{-e^{-W_1(t-T)} - W_2(t-T)} \tag{6}$$

Unfortunately, the outlet pulse $C_{out}(t)$ comprise the dispersion of the initial pulse caused by the connecting pipes between injection valve and the first photometer as well as the RTD characteristic of the micromixer. Both effects can be separated by the help of a mathematic deconvolution of both signals. Therefore, the deconvolution integral Eq. (3) has to be solved. $E(t)$ represents the desired residence time distribution which is responsible for the changes between input and output traces.

The direct deconvolution of the tracer signals reveals not a unique functional relation because the intrinsic noise in the measurement signals leads to insignificant results [6]. To overcome this problem, a model based technique for the calculation of the RTD was used. Therefore, an appropriate RTD model has to be chosen before. The RTD function of the fluid system between the first and the second measurement position (photometers) can be derived from both the tracer profiles by using the dispersion model [7]. For the determination of the best RTD the model parameters have to be varied successively to find the optimal correlation between C_{out}^{calc} and C_{out} (Eq. (4)). This optimization procedure has to be done in order to minimize the sum of squares ε (Eq. (5)) and leads to more or less fitting calculated response curves depending on the used model. We choose the empiric model (Eq. (6)) for the description of the RTD function in order to describe microdevices more precisely. The model parameters W_1, W_2, and T are not connected to physical parameters. But, Eq. (6) described the RTD $E(t)$ better than the dispersion model for all investigated experiment. The residence time characteristic of the microdevices was measured by the residence time distribution in dependence on dimensionless time. The dimensionless time Θ is given by the quotient of measurement time t and the mean residence time τ (Eq. (7)). The mean residence time was calculated as the first momentum of the RTD (Eq. (8)). The dimensionless time Θ enables the direct comparison of the RTD received for different flow rates.

$$\Theta = \frac{t}{\tau} \tag{7}$$

$$\tau = \int E(t) \cdot t \cdot dt \tag{8}$$

3.1. *Statmix6*

The comparison between the measured traces signals C_{out} and the calculated C_{out}^{calc} for different fluidic conditions prove the applicability of the chosen model. The shape of the measured tracer profiles and the experimentally determined RTD function varies considerably with flow rate and viscosity. At low flow rates and low viscosity, the tracer profiles at the input photometer and at the outer photometer position shows only a slight asymmetry. The chosen model reflects very well the device RTD under the differ-

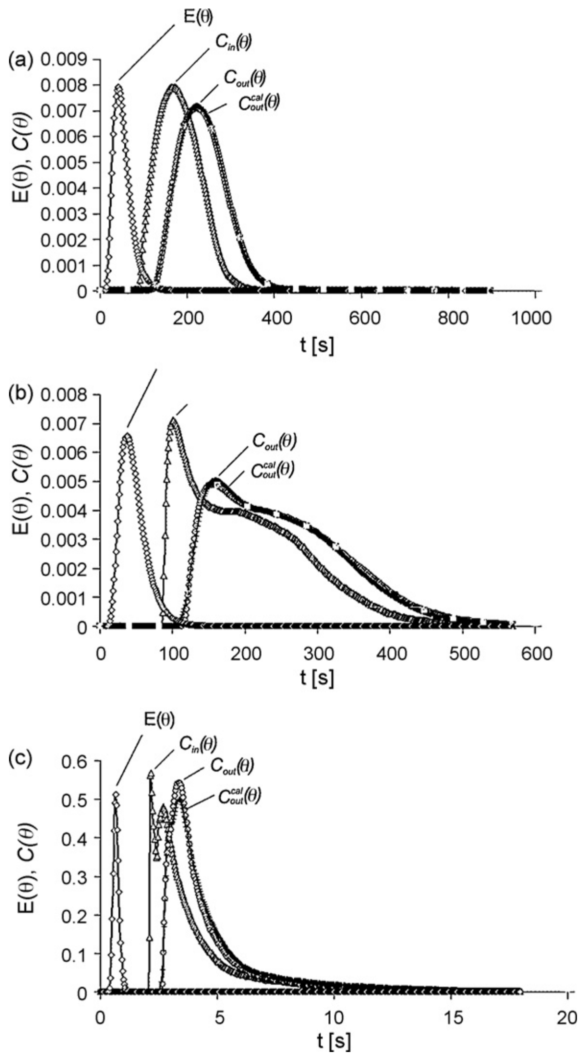

Fig. 2. Application of the dispersion model for the residence time characterization of the static micromixer Statmix6 for different fluidic conditions: comparison between normalized profiles; calculated RTD $E(t)$, inlet sensor signal $C_{in}(t)$, calculated outlet sensor signal $C_{out}^{calc}(t)$ and measured outlet signal $C_{out}(t)$: (a) pure water, 50 μL/min, (b) 40% glycerol in water, 50 μL/min, and (c) 40% glycerol in water, 3000 μL/min.

ent conditions (Fig. 2a). A massive shoulder was found in the outlet trace in case of enhanced viscosity (Fig. 2b). The much lower asymmetry in the measured input trace suggests a cumulative effect on the shoulder by the residence time characteristic of the static micromixer, which is well described by the calculated RTD function. The shoulder of the outlet trace is converted into a double peak in case of high flow rates and enhanced viscosity. Even in this case, the used model (Eq. (7)) gives a nearly perfect description of the RTD (Fig. 2c).

At low flow rate (100 μL/min), only a very small effect of the viscosity on the residence time distribution was observed (Fig. 3a). Obviously, the flow regime in this case was nearly independent on the viscosity. This situation changed if the flow rates are enhanced. At 800 μL/min, the shape of the determined RTD became significantly influenced by the viscosity. The asymmetry of RTD curve increase with increasing viscosity (Fig. 3b) and the RTD of the static micromixer Statmix6 shows a clear dependence on flow rate. At lower flow rates (50–400 μL/min) the RTD of a water/glycerol mixture containing 10% glycerol is asymmetric, resulting in an early maximum and a significant RTD tailing (Fig. 4). At higher flow rates (800 μL/min and above), the RTD becomes more symmetrically and the tailing is considerably reduced. The differences between the

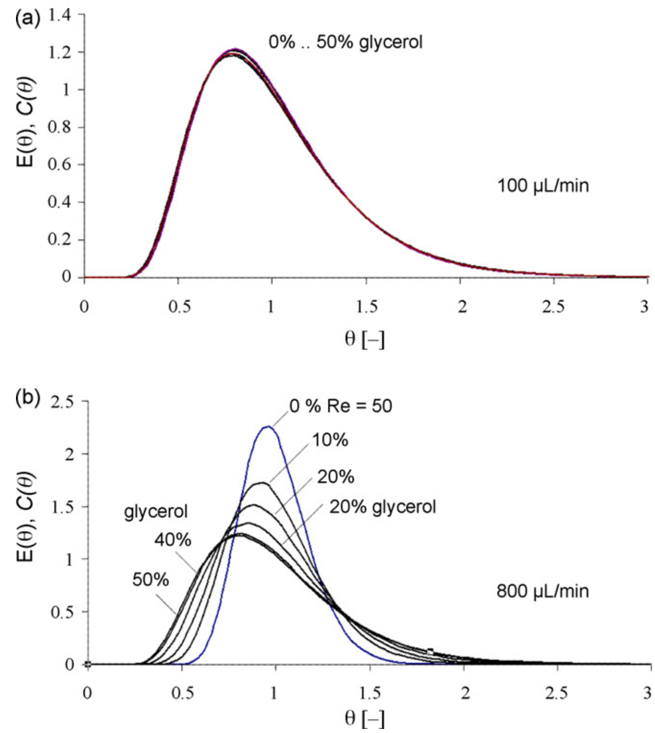

Fig. 3. Effect of viscosity at low and mediate flow rates for the RTD $E(\Theta)$ of the static micromixer Statmix6: (a) lower flow rate (100 μL/min, Re < 10) and (b) higher flow rate (800 μL/min, Re = 10–50).

RTD at higher and lower flow rates were reduced if the viscosity was enhanced. The change of flow rate influence becomes clear by comparison of RTDs obtained in a lower and a higher flow rate range at a glycerol content of 40%. Nearly no significant flow rate effect was found at flow rates between 50 μL/min and 1 mL/min (Fig. 5a). The residence time distribution in the static micromixer seems to be unaffected by the flow rate in this range. The situation was changed if the flow rate was increased further on. The RTD becomes sharper and tends to more and more symmetric shape with increasing flow velocity (Fig. 5b). We assume that in case of lower flow rates a strong laminar regime dominates the channel system of split and recombine units and the system behave like a channel with constant dispersion. Apparently, secondary flow is induced by increasing flow rate and the vortices reduce the dispersion as observed in Fig. 5b.

The transition between both types of flow regimes are well reflected by the dependence of the RTD tailing factor Θ_{99} (Eq. (1)) on the flow rate. Θ_{99} was slightly reduced with increasing flow rates in the lower flow rate range, and is followed by a steep

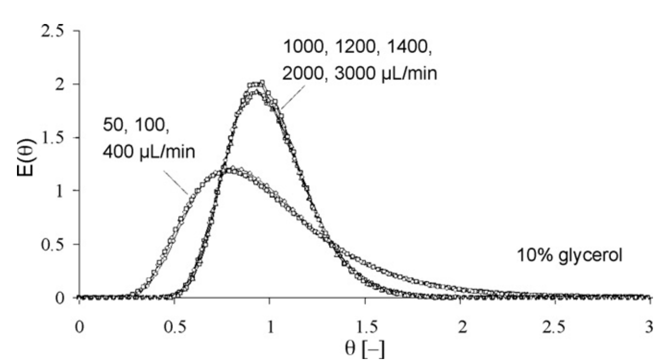

Fig. 4. RTD $E(\Theta)$ of the static micromixer Statmix6 at 10% glycerol: flow rate effect at moderate viscosities (50 μL/min, Re > 10; 3000 μL/min, Re = 150).

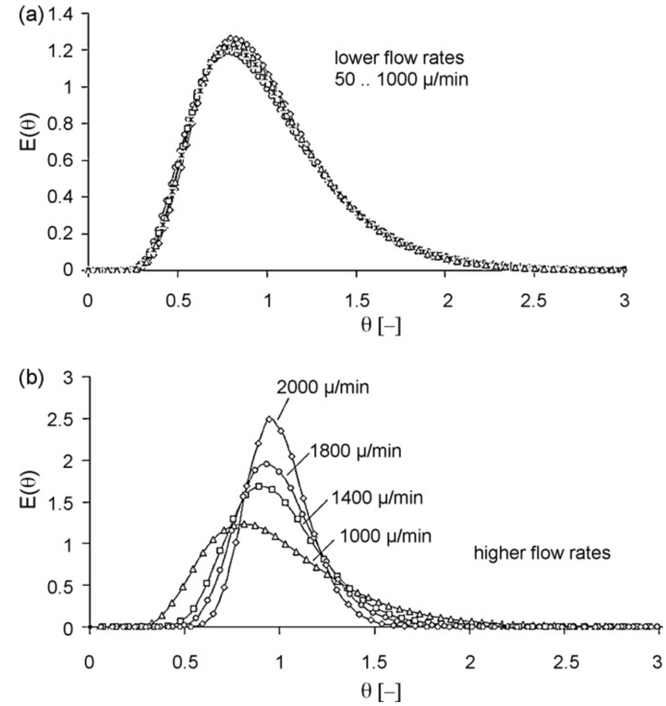

Fig. 5. Normalized RTD $E(\Theta)$ of the static micromixer Statmix6 at 40% glycerol: (a) constant RTD at lower and mediate flow rates (Re < 20) and (b) changing RTD at higher flow rates (Re = 20–40).

decrease at enhanced flow rates (Fig. 6a). This characteristic was qualitatively independent on the viscosity, but the steep decrease shifts to higher flow rates if the viscosity was enhanced. This characteristic reflects a viscosity dependence of transport mechanism which can be described by the help of the Re number. A monotonic Re number dependence was found for lower and mediate viscosities (0–30% glycerol in water). But, at higher viscosities (40

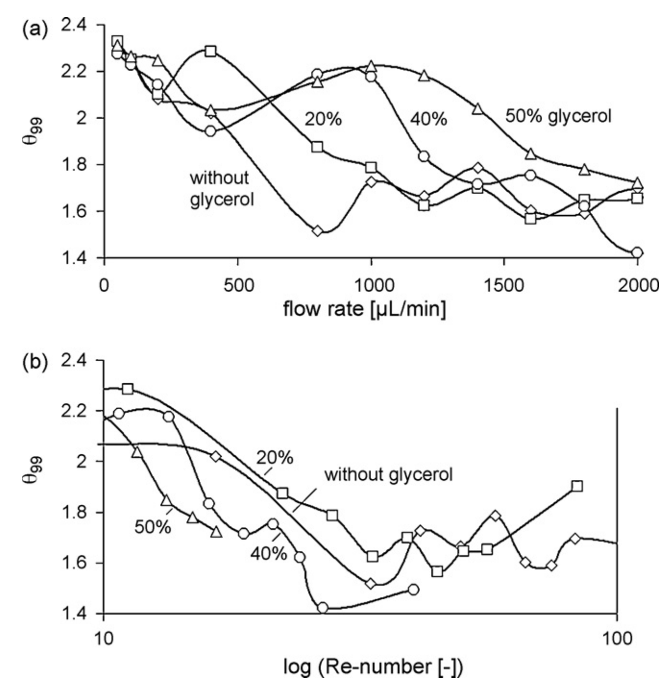

Fig. 6. Tailing characteristic of the static micromixer Statmix6 in dependence on flow rates and viscosity: (a) effect of flow rate for different glycerol content on tailing factor Θ_{99} and (b) dependence of tailing factor on Reynolds number.

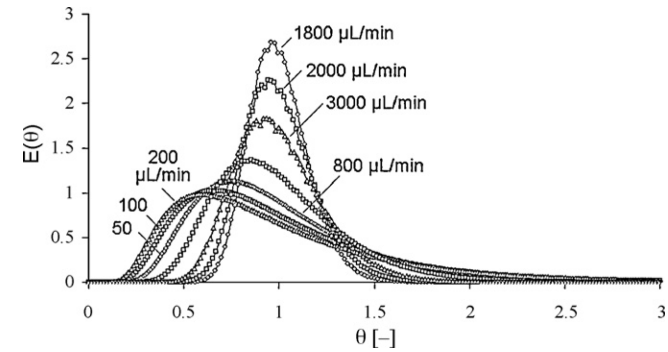

Fig. 7. Non-monotonic shift of the RTD with flow rate for the mikroglass micromixer at moderate viscosity (10% glycerol in water, Re < 60).

and 50% glycerol) the transition between the both types of RTD characteristic was observed at lower Re numbers as expected (see Fig. 6b).

3.2. Mikroglas interdigital mixer

The static mixer of mikroglas possesses a more complex residence time characteristic. On the one hand, there were found two types of RTD characteristics analogously to the Starmix mixer. We have to consider that the construction of the mixer contains two inlet channels which guide the fluid to the interdigital mixing structure. These channels take a significant influence on the RTD and cannot be neglected. Nevertheless, we characterized the micromixer as entire device. We found that there was a significant non-monotonic dependence of the RTD on flow rate (Fig. 7). An increasing asymmetry was observed with increasing viscosity at low flow rate (Fig. 8a). The maximum of the RTD shifts from about $\Theta = 0.9$ for pure water to about $\Theta = 0.5$ in case of 50% glycerol. The shift direction changes direction at higher flow rates. The differences for different viscosities are reduced, but the highest asymmetry of RTD function arised at lower viscosity in this case (Fig. 8b). At lower viscosities (0–20% glycerol), this

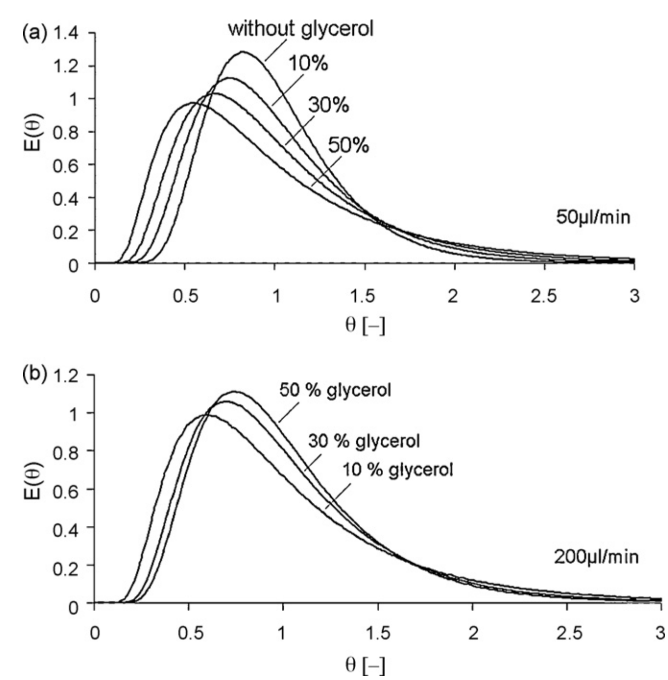

Fig. 8. Effect of viscosity on the RTD of the mikroglass micromixer for different flow rates: (a) 50 μL/min, Re < 2 and (b) 200 μL/min, Re < 10.

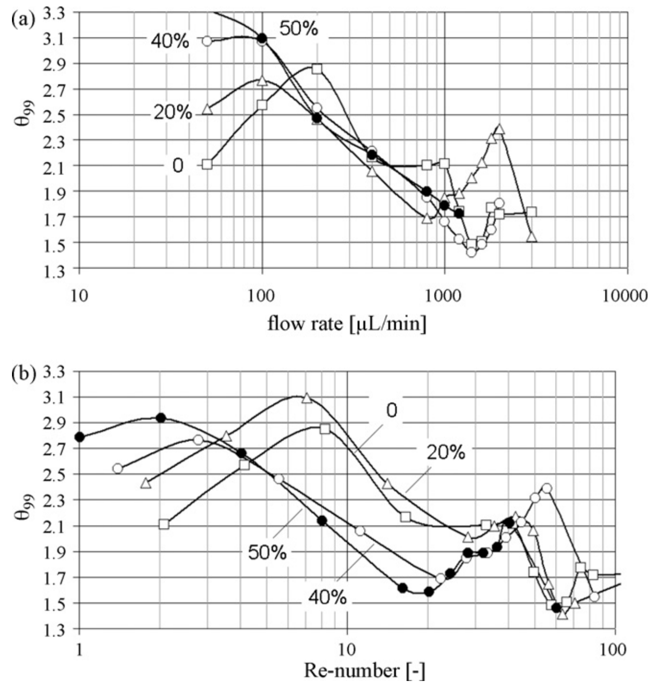

Fig. 9. Dependence of tailing factor Θ_{99} on flow rates and viscosities for the mikroglass micromixer.

non-monotonous behaviour is reflected by the appearance of a maximum in the tailing factor Θ_{99} in front of the steep decrease with increasing flow rate (Fig. 9a). The transition between the more asymmetric and the more symmetric RTD (higher and lower tailing) is nearly independent on the viscosity in the investigated flow rate range. The dominating role of the flow rate and the nearly negligible influence of the viscosity for this transition demonstrates the comparison between the flow rate dependency and the Re number dependency of the tailing factor Θ_{99} (Fig. 9b). A non-monotonic characteristic of the RTD was explained by Kockmann by flow rate dependent changes in the flow regime inside microfluidic channels such as the engulfment flow [3,16].

The complex RTD characteristic is not originally caused by specific complex structures of mixing devices. They were qualitatively observed in different microreactors [6,10,17]. They were also observed in more simple fluidic systems like a PTFE tube with an ideal circular shaped cross-section. It is obvious that the fluid channels inside the mixer before the mixing structure itself have a stronger influence on the total mixer residence time characteristic.

3.3. PTFE-tubing

In case of a straight 40 cm PTFE-tubing (1 mm ID) small RTDs were found at high viscosities and high flow rates. For the fluidic connection standard ferrule connectors made of ETFE were used. The RTD becomes broader with increasing flow rates, but the character of the RTD is only less affected by flow rates in the high flow rate range (Fig. 10). Decreasing the flow rate below 0.4 mL/min results in broad RTDs. The strong change in the character of RTD indicates a transition in transport mechanism principle between flow rates about 0.1 and 0.4 mL/min. A complex RTD response of the arrangement with the PTFE tube was also reflected at lower viscosity. Between 50 and 100 μL/min the RTD becomes asymmetric and a shift of the RTD maximum to shorter Θ time take place. At mediate flow rates the RTD maximum shifts to higher Θ values and becomes less asymmetric, at high flow rates the asymmetry increased again. A nearly symmetric RTD was obtained at mediate flow rates in the range of about 400 μL/min (Fig. 11a). At

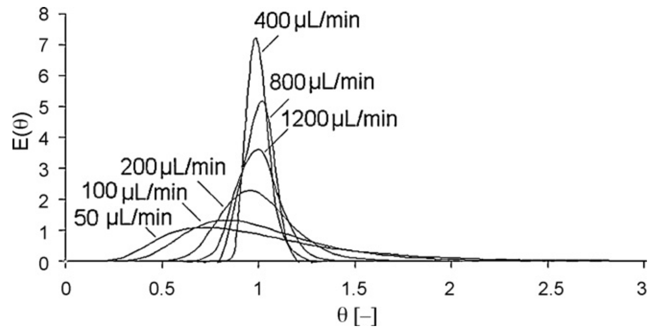

Fig. 10. Effect of flow rate on the shape of the RTD for a straight PTFE tube at high viscosity (50% glycerol in water (Re < 30), internal diameter of tube: 1 mm, tube length: 40 mm).

higher flow rates, and lower viscosity (10% glycerol) the situation was completely different (Fig. 11b). The RTD is rather asymmetric, but the flow rate dependence disappears completely. The change in the flow regime is also well reflected for the RTD in dependence on viscosity. At low flow rates (50 μL/min), the RTD is very broad, asymmetric and shifts to slightly reduced asymmetry with increasing viscosity (Fig. 12a). At enhanced flow rates (1 mL/min) large differences were observed between low and high viscosities (Fig. 12b). Small RTDs were found at high viscosity (40–50% glycerol). Further enhancements of flow rates draw the RTD for mediate viscosity back to higher asymmetry (Fig. 12c). This characteristic behaviour cannot simply be described by a monotonic Re number dependence. The characteristic decrease of the tailing factor Θ_{99} in dependence on the Re number shifts with increasing viscosity (Fig. 13). This observation confirms the experimental observation that not only the complex micromixer geometries are responsible for significant changes in the RTD characteristic and the non-monotonous dependencies of the tailing factor but also spontaneous change of the transport mechanisms inside microchannels take place. This observation matches to the general fluidic phenomenon that low Re numbers are connected with more ideally

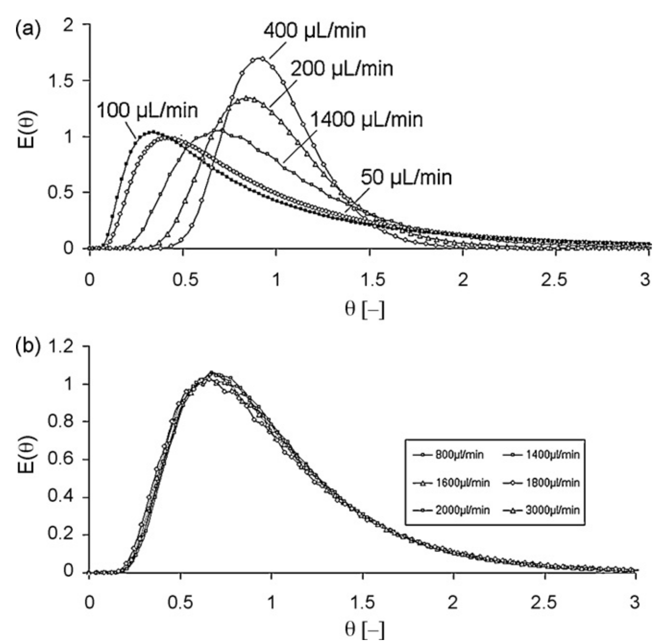

Fig. 11. Effect of flow rate on the shape of RTD of a PTFE tube at moderate viscosity (10% glycerol in water, internal diameter of tube: 1 mm, tube length: 40 mm): (a) changing RTD at low and mediate flow rates, Re < 30 and (b) nearly constant RTD at high flow rates, Re = 30–60.

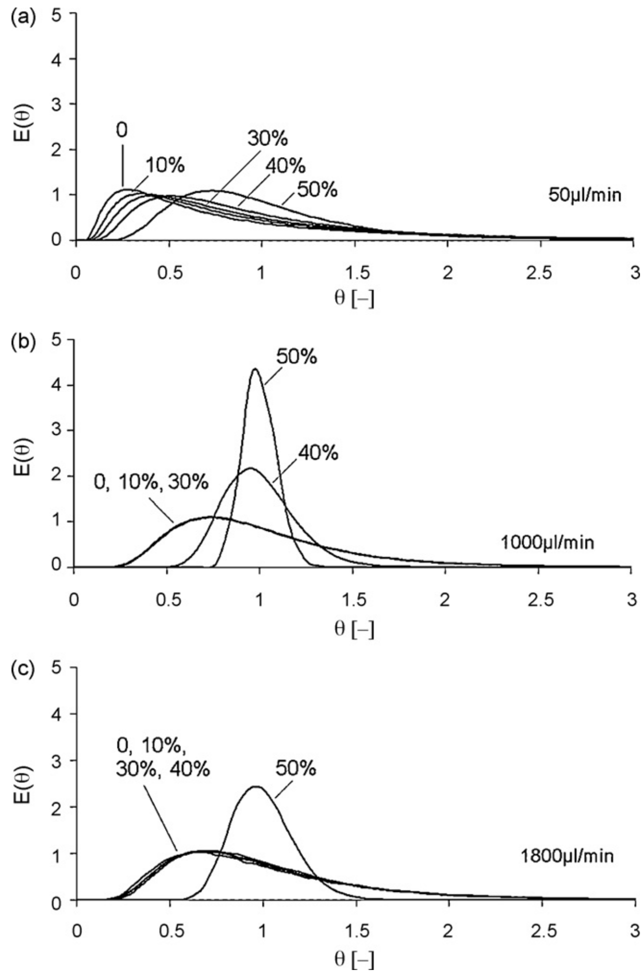

Fig. 12. Effect of viscosity (glycerol content in water) on the RTD of a PTFE tube (internal diameter of tube: 1 mm, tube length: 40 mm): (a) at low flow rate (50 μL/min), Re < 2, (b) at mediate flow rate (1000 μL/min), Re < 25, and (c) at higher flow rate (1800 μL/min), Re < 50.

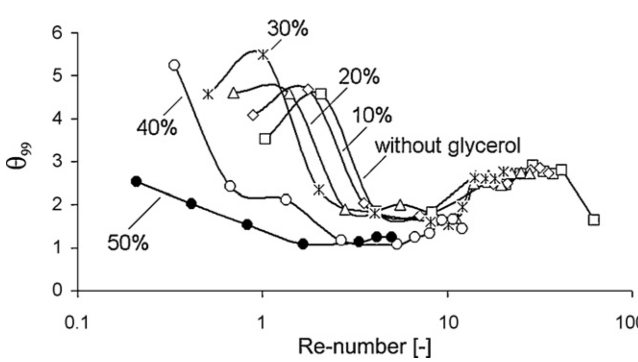

Fig. 13. Dependence of the tailing factor Θ_{99} on the Re number for the PTFE tube (internal diameter of tube: 1 mm, tube length: 40 mm) in case of different viscosities.

laminar flow and higher Re numbers with higher hydrodynamic complexity such as engulfment flow regimes.

4. Summarizing conclusions

The RTD characteristic is one of the most important parameter for chemical reaction engineering. In microprocess engineering the mean residence times may be short but the RTD of microdevices has to be taken into account too. For fast chemical reactions such as the formation of nanoparticles [14,15] the RTD is directly connected with the product quality. For a better understanding of the viscous flow tree microdevices were studied and their characteristics show. The flow rate and viscosity dependent RTD of the static micromixer Statmix6, the mikroglas interdigital mixer and straight PTFE tube were characterized by a microfluidic arrangement using a pulse trace method and two fast scanning microphotometers. The micromixing devices show a significant change in the RTD in dependence on flow rate. Higher symmetries in the RTDs were found at high flow rates and large tailing factors Θ_{99} at low flow rates. The RTD characteristic for low flow rates and viscosities can be described by the Re number in case of the Statmix6 mixer. Different characteristics were found in case of the mikroglas mixer and in case of a simple PTFE tube. The investigations show that beside the Re number the viscosity as well as the flow rate has to be considered carefully for the residence time characteristic of a microdevices or assembly.

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