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On the scalability of microstructured mixing devices☆

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ABSTRACT

Microchannel systems for multilamination mixers can be obtained by stacking and bonding microstructured foils. So-called V-type mixers have been manufactured and examined at the Institute for Micro Process Engineering by means of the Iodide Iodate Reaction Method. In previous work we showed that V-type mixers can be scaled by varying the number of micromachined foils and holding constant velocities of the fluids exiting the microchannel system. Applying the Iodide Iodate Reaction Method, constant triiodide concentrations, indicating constant 'mixing qualities', were obtained with mixer inlays with 6 foils, 12 foils, and 24 foils. In order to understand the influence of the top- and the bottom foils, which are different regarding their geometrical environment, examinations are presented with mixer inlays with 4 foils and 2 foils. The two newly examined inlays are fully 'in-line' with the scaling considerations from the previously examined devices. An influence of the boundary foils cannot be shown.

Furthermore, it is shown that the arrangement of the microchannels at the interface between the microchannel system and the mixing chamber ('shape of the exit window') has a crucial impact on the mixing results: the larger the width of the exit window, the better the mixing results.

1. Introduction

Microstructured mixing devices possess numerous advantages on the laboratory scale. The development of microstructured mixing devices for industrially relevant throughputs has rarely been reported, and the corresponding upscale is still a challenging task. In a previous publication V-type mixers were presented that could be scaled to higher mass flow throughputs by adding additional microstructured foils (keeping a constant number of microchannels per foil) while maintaining a constant 'mixing qualitiy' of the resulting mixtures [1]. In this contribution we present investigations of V-type mixers with a minimal number of foils (2 foils, 1 foil per passage). This is an important investigation concerning the scalability of V-type mixers because the bottom and the top foils (boundary foils) differ in geometrical environment from the 'core foils'.

Compared to scaling of mixing processes in macroscopic stirred vessels and pipeline mixers [2] no equivalent concepts are available for microstructured mixers. Processes in microstructured devices can be scaled by external numbering-up, the parallel repetition of process units to achieve high throughput. This approach requires a liquid-flow splitting unit [3] and a multitude of devices. Limitations of this approach due to flow maldistribution are reported in the literature [4]. The approach of external numbering-up is limited to process development [5]. For the scientific examination of mixing processes in microstructures, no additional information can be gained using this approach. A concept similar to the one given in this contribution is reported by Men et al. [6]. They report on a class of geometrically similar mixers denoted 'StarLaminator' (available in different sizes abbreviated StarLam30, StarLam300, StarLam3000 and StarLam30000). These mixers consist of two kinds of structured disk-shaped foils, separation foils, and mixing foils, which are alternately stacked. The size of a mixer can be varied by the number of foils. Men et al. [6] have shown on the example of the StarLam300 that a mixing device can be scaled by the 'flow rate per foil'. Their approach is an example for internal numbering-up since the size of the mixing chamber is directly proportional to the height of the stack of foils.

2. The mixing devices

V-type mixers and their capability to mix gases were described earlier [7,8]. In a recent publication the authors [1] reported on their properties for liquid–liquid mixing. V-type mixers are obtained by stacking micromachined foils and bonding them (Fig. 1).

Due to the construction the fluids exit the microchannel system with an angle of 45° to the interface of the microchannel system to the mixing chamber and with an angle of 90° to each other. This fact is not beneficial for mixing since the fluids partially 'resegre-

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☆ *Note*: Preliminary results to this contribution have been presented at the International Conference on Microreaction Technology (IMRET 10) held in New Orleans (April 6–10, 2008) [26].

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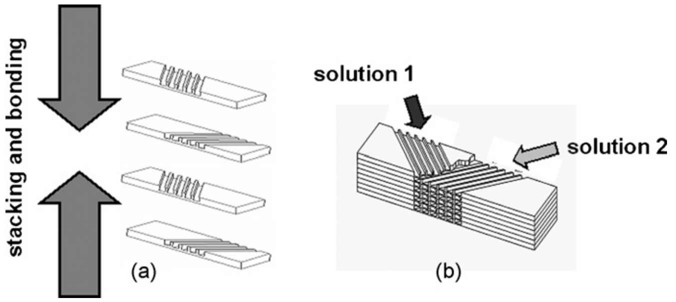

Fig. 1. Construction principle of microstructured V-type mixers: (a) stainless steel foils with microchannels and (b) stack of stainless steel foils.

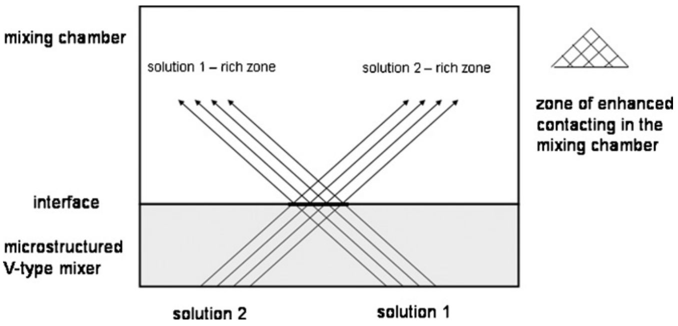

Fig. 2. Schematic representation of the mixing process using V-type mixers.

gate' in the mixing chamber after having passed a 'zone of enhanced contacting'. This mechanism has been demonstrated for V-type mixers with numerical simulations in another study [9]. These considerations are demonstrated two-dimensionally in Fig. 2. For the three-dimensional case, the volume of a triangular prism can be calculated for the 'zone of enhanced contacting'.

The microchannels are milled in stainless steel foils. The foil thickness for V-type mixer inlays investigated here is 200 μm. The cross-section for the micromachined channels is 100 μm × 70 μm. Fig. 3 shows the exit of a stack of foils with construction parameters relevant to this study.

The resulting mixer stacks can be fitted inside a flange adapter constructed of stainless steel (Fig. 4).

The flange adapter can be attached conveniently to the experimental set-up (see Section 4.2) via Swagelok fittings. The circular mixing chamber has a diameter of 8 mm and a depth of 8 mm and is machined in the flange adapter (Fig. 4). At the end of the mixing chamber, the inner diameter is reduced to the diameter of the tubing (4.8 mm).

V-type mixers are assumed to work according to the multilamination principle [10]. The microchannel system subdivides the fluids into a number of substreams. Those substreams are recombined layerwise in a mixing chamber. If diffusion is the dominant mixing mechanism, the theoretical diffusion length of reactants from adjacent layers is 50% of the layer thickness (Fig. 5).

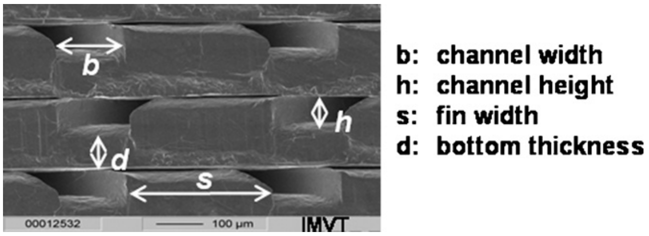

Fig. 3. Stack of foils with indication of relevant construction parameters.

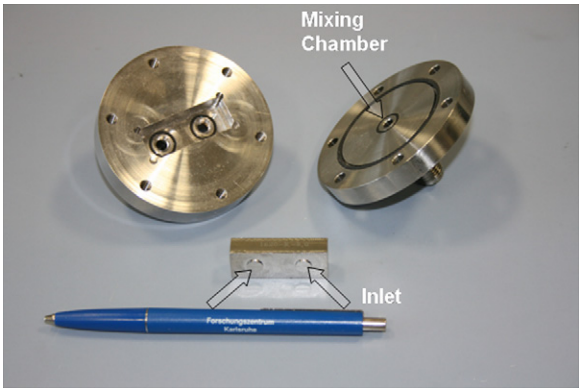

Fig. 4. Flange adapter and micromixer inlay.

The top and the bottom layers are different with respect to the theoretical diffusion length. The theoretical diffusion length would be 100% of the layer thickness if the mixing chamber had the same dimensions as the 'window' of the exiting fluids. Since the cross-section of the larger mixing chamber is much bigger than the cross-section of the 'exit window', the discrepancy in both path lengths is even larger.

3. The examination method

Mixer characterizations were carried out with the Iodide Iodate Reaction Method. The Iodide Iodate Reaction Method is based on the competition of two reactions: (a) a neutralization reaction and (b) the comproportionation of iodide and iodate to form iodine, also referred to as the Dushman reaction [11]:

$$H_2BO_3^- + H^+ \rightarrow H_3BO_3 \tag{a}$$

$$5I^- + IO_3^- + 6H^+ \rightarrow 3I_2 + 3H_2O \tag{b}$$

Using the Iodide Iodate Reaction Method, two solutions of reactants are mixed. One solution contains H^+, the other solution contains the rest of the chemicals essential for the reactions (a) and (b). Thus, both reactions are initiated at the onset of the mixing process. In case of perfect mixing, the composition of the resulting mixtures is governed solely by the kinetics of the chemical reactions involved, and virtually no iodine is formed. For real mixing processes, the composition of the resulting mixtures is influenced by both the kinetics of the chemical reactions and the hydrodynamics of the mixing process. More efficient mixing processes prefer reaction (a), less effective mixing processes prefer reaction (b). Iodine, which is produced in course of the mixing process, further reacts with excess iodide to form triiodide according to equilibrium (c).

$$I_2 + I^- \rightleftarrows I_3^- \tag{c}$$

Triiodide can easily be determined photospectrometrically in the UV range at its absorbance maxima of 286 and 353 nm. Thus, mixing processes can be evaluated by the optical densities of the resulting mixtures at the respective wavelengths. Other research groups have proposed further mixing parameters, which derive from the optical densities, namely, a 'segregation index', X_S [12]; a 'micromixedness ratio', α [12]; and the 'mixing time', t_m [13].

The Iodide Iodate Reaction method was originally developed for stirred laboratory tanks [14,15] and later adapted for the needs of continuous flow mixers [16]. The Iodide Iodate Reaction Method is a reliable characterization method for parametric studies. Mixing devices and processes can be qualitatively compared by means of the Iodide Iodate Reaction Method. Lower triiodide concentrations in the resulting mixtures (product of the slower reaction) indicate better mixing processes. Thus, the influence of structural

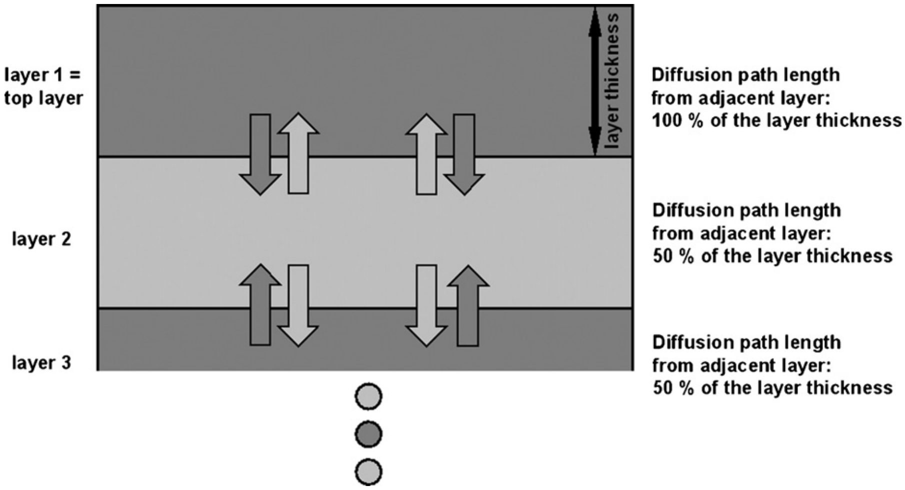

Fig. 5. Schematic of the exiting layers of the fluids.

parameters upon the mixing process can be investigated. In a recent publication on V-type mixers [1], the fin width was identified as an influential parameter.

For the quantitative scaling of devices, it is necessary to understand the relationship between the variables describing mixing and the triiodide concentrations in the resulting mixtures. An approach towards the description of such a relationship has been given by the working group of L. Falk in Nancy, France, who derived 'mixing times, t_m,' from experimentally determined triiodide concentrations in the resulting mixtures. Mixing times from mixing experiments in stirred vessels are derived from the incorporation model [15,17,18]. Mixing times from experiments in microstructured continuous flow mixers are derived from the IEM model (**I**nteraction by **E**xchange with the **M**ean) [13,19]. It should be noted that those mixing times are parameters in the respective models. According to Falk and Commenge [19], the mixing times derived from the IEM model deliver "the order of magnitude of mixing time for practical applications". The mixing times reported scale roughly linearly with the optical densities of the resulting solutions. The accuracy of this approach might be limited by the fact that the kinetic data of the Dushman reaction were collected at reactant concentrations far from those relevant to mixing studies [20,21]. Furthermore, it is shown in a recent study [22] that either the dissociation constants of sulfuric acid need to be included in the respective models or strong acids such as perchloric acid need to be used in the experiments, in order to provide an accurate quantitative description of mixing processes with the Iodide Iodate Reaction Method. Despite the shortcoming that the Iodide Iodate Reaction Method does not offer a reliable quantitative measure of mixing, the method can be used for scaling issues, when in case of a family of curves, representing the optical density of the resulting solutions as function of an independent variable, another independent variable can be found, which combines the family of curves to one single curve. This approach assumes that the composition of the resulting mixtures is characteristic for the hydrodynamics of the mixing process in sense of a characteristic mixing time. This assumption should be justified in geometrically similar mixers in scaling studies. The approach of combining a family of curves in one curve has been given in a previous study [1] by the authors, when showing, that V-type mixers can be scaled by varying the number of micromachined foils. When plotting the obtained optical densities of the resulting mixtures as a function of the total mass flow rate, a family of curves is obtained. When plotting the obtained optical densities of the resulting mixtures as a function of the linear velocity of fluid in the microchannel system, one curve is obtained (see Section 5.1.1). A similar approach has been done by researchers of the IMM (Institut für Mikrotechnik Mainz GmbH, Mainz, Germany) on the example of the StarLam 300 mixer (see Section 1 [6]).

4. Experimental conditions

4.1. Reactant concentrations

The authors have shown [1,23] that the reactant concentrations must be carefully chosen in order to obtain mixing sensitive results. For the present study the application of the standard concentration (1SC) was sufficient. The respective concentrations are summarized in Table 1.

All mixers are compared by combining those solutions at equal flow rates.

4.2. Experimental set-up

A schematic of the experimental set-up is given in Fig. 6.

The experimental set-up is constructed in stainless steel. The fluids are pumped with annular gear pumps (HNP Mikrosysteme GmbH, Parchim, Germany, mzr type 7206). Their flow is monitored with Coriolis flow meters (Endress und Hauser, Reinach, Switzerland, Promass 63). The temperature of the solutions is maintained at 20 °C with a circulating bath (Thermo Haake GmbH, Karlsruhe, Germany, DC50/K20) and microstructured heat exchanger (IMVT, Karlsruhe Institute of Technology, Germany). The pressure is measured with electric pressure transducers (Baumer Bourdon-Haenni AG, Jegenstorf, Switzerland, E913). The resulting mixtures are collected at the exit of the experimental set-up and a UV spectrum is recorded (Agilent Technologies, Santa Clara, USA, HP 8453).

Table 1
Reactant concentrations used for this study.

	Concentrations
Solution 1	
Sulfuric acid	0.03 mol/L
Solution 2	
Potassium iodide, KI	0.016 mol/L
Potassium iodate, KIO_3	0.003 mol/L
Sodium hydroxide, NaOH	0.045 mol/L
Hydroboric acid, H_3BO_3	0.045 mol/L

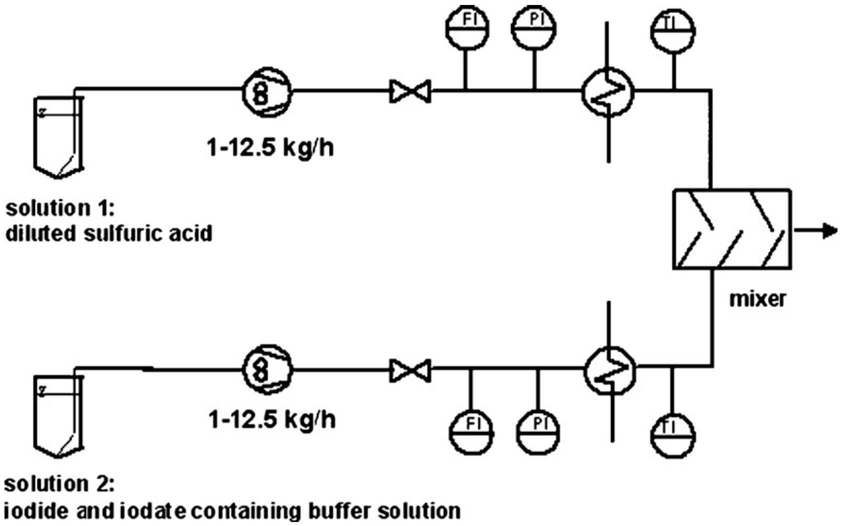

Fig. 6. Schematic of the experimental set-up.

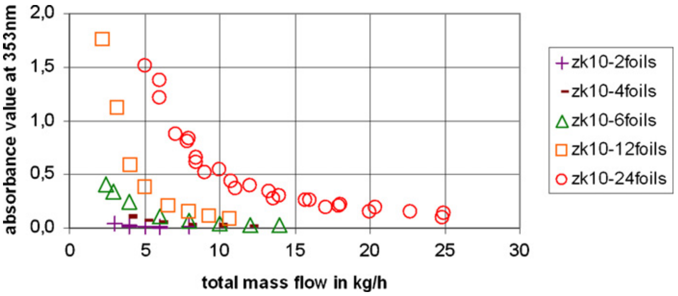

Fig. 7. Experimental characterization of V-type mixers: optical densities of the resulting solutions over total mass flow rates.

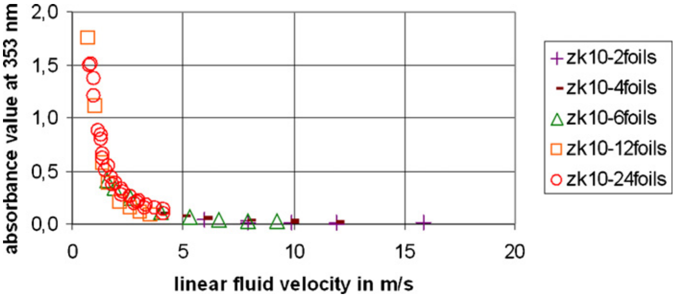

Fig. 8. Optical densities of the solutions plotted with respect to the linear velocities of the fluids exiting the microchannel system.

5. Experimental results and discussion

5.1. *Variation of the foil number*

5.1.1. *Mixing characterization*

It was shown in a previous publication [1] for constant mass flow rates, that a smaller number of microchannels improves mixing, indicated by lower optical densities of the resulting mixtures (Fig. 7). This benefit is obtained at the cost of higher pressure drops [1]. The pressure drop for a total mass flow of 5 kg/h for instance was determined to be 1.23 bar for the mixer z_k10-12foils (120 microchannels) and 0.57 bar for the mixer z_k10-24foils (240 microchannels).

We showed that V-type mixers can be scaled to higher and lower mass flow rates by varying the number of microstructured foils, keeping a constant velocity of the exiting fluids. This was done by comparing devices with 6 foils (3 foils per passage), 12 foils (6 foils per passage), and 24 foils (12 foils per passage). All other parameters were kept constant (fin width (s): 100 μm; channel cross-section ($b \times h$): 100 μm × 70 μm; bottom thickness (d): 130 μm; number of channels per foil (z_k): 10). Thus, the structure of every single foil was kept constant. Furthermore, no particular attention was paid to a possible influence of structural details of the microstructured foils on the mixing results, although it was recognized that bigger fin widths favor mixing. Plotting the optical densities of the resulting solutions over the linear velocity of the exiting fluids, all measurement points yielded in the previous study [1] a common curve (Fig. 8, z_k10-6foils, z_k10-12foils, z_k10-24foils).

When investigating the scaling of multichannel systems, the "boundary" can pose a problem. This is due to the fact that the gradients for mass or heat transfer are different there (see Fig. 5). In a previous study [1], micromixers with 6, 12, and 24 foils have been investigated. Even considering the case of 6 foils, 2/3 of channels or the majority have symmetrical boundary conditions. To investigate how the perimeter layers influence the gross result, two new V-type mixers with 2 and 4 foils, respectively, have been manufactured and tested. Characteristics of V-type mixers previously (z_k10-24foils, z_k10-12foils, and z_k10-6foils) and newly (z_k10-4foils and z_k10-2foils) characterized are listed in Table 2.

Table 2
Characteristics of V-type mixers previously and newly examined.

	Total number of foils	Foils per passage	Number of inner foils	Number of boundary foils	% of channels in boundary foils
z_k10-24foils	24	12	22	2	8
z_k10-12foils	12	6	10	2	17
z_k10-6 foils	6	3	4	2	33
z_k10-4foils	4	2	2	2	50
z_k10-2foils	2	1	0	2	100

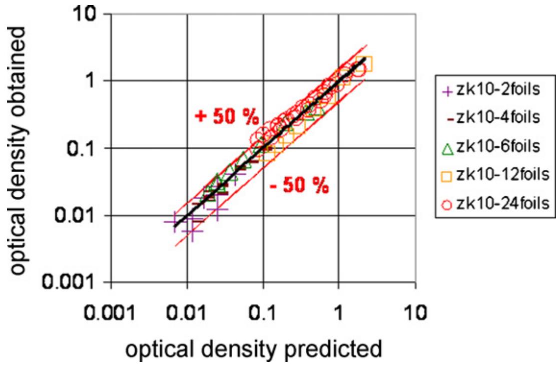

Fig. 9. Parity plot for the variation of the number of micromachined foils of V-type mixing devices.

Fig. 8 further shows that the newly constructed devices are fully 'in-line' with the devices previously examined. Devices, containing between 2 and 24 micromachined foils can therefore be scaled over the linear velocity of the fluids exiting the microchannel system. This experimental finding can be more distinctly demonstrated by the parity plot of the experimental results (Fig. 9).

An empirical expression ('best fit') representing all optical densities as a function of the total mass flow (Eq. (d)) has been derived as follows:

$$\mathrm{OD} = 1.24\left(\frac{dm/dt}{0.0252 n_c (\mathrm{kg/h})}\right)^{-1.88} \tag{d}$$

Eq. (d) relates the optical densities of the resulting solutions with the total mass flow rate (dm/dt in kg/h) and the total number of channels (n_c). The expression in the bracket relates the mass flow in kg/h to the linear velocity of the fluids in the channels. Eq. (d) contains two adjustable parameters which were calculated to be 1.24 and −1.88 in order to obtain minimized differences between the optical densities predicted by this equation and the measured optical densities. The obtained optical densities as function of various mass flow rates are given as function of the optical densities expected from Eq. (d) in the parity plot (Fig. 9). The error range is given with +/− 50%. Within this range no systematic deviation of the single devices could be found. The scattering of the depicted experimental values might reflect the accuracy of the method and manufacturing tolerances for the devices.

The expected decrease in the mixing quality when lowering the number of foils to a minimum (2 foils) could not be found. The experimental findings indicate, that a diffusion-mixing model as introduced in Section 1 is a too simplistic view for the mixing process. This experimental finding can be understood by the assumption that macromixing with creation of substantial interface area is taking place before significant diffusion occurs. The newly created interfacial area is then much larger than the interfacial area right at the exit of the fluids into the mixing chamber, so that this 'original' interfacial area is no longer characteristic for the composition of the resulting mixtures. Most of the pressure drop (Section 5.1.2) is created in the microchannel system before the liquids are contacted in the mixing chamber. Characteristic for the mixing process is the pressure drop induced energy dissipation in the mixing chamber. The irreversible pressure drop due to an abrupt flow area increase is given in the literature [24] Eq. (e):

$$\Delta p_{\mathrm{irr}} = K_e \frac{1}{2}\rho\frac{u^2}{2} (\text{in Pa}) \tag{e}$$

The expansion loss coefficient K_e is a function of the ratios of the cross-sections. For small cross-section ratios ($A_1/A_2 \rightarrow 0$) K_e equals 1. The ratios of the cross-sections of the devices are listed in Table 3.

Dividing Eq. (e) by the density ρ yields the dissipated energy per mass unit (Eq. (f)):

$$E_m = \frac{1}{4}u^2 (\text{in J/kg}) \tag{f}$$

Scaling by numbering identical microstructured foils can thus be understood by considering the fact that the dissipated energy per mass unit only depends on the linear velocity of the fluids in the microchannel system, regardless of the number of foils stacked.

Increasing the number of microstructured foils leads then to an increasing throughput at constant energy dissipation per mass unit.

5.1.2. Pressure drop measurements

Another important scaling parameter is the pressure drop occurring in mixing devices and its relation to the flow throughput. It is assumed that the pressure drop occurs mainly in the microchannel system (neglecting the pressure drop in the mixing chamber) and the fluid flow is laminar. The pressure drop in a smooth pipeline with a circular cross-section can be derived by Eq. (g) [25]:

$$\Delta p = \zeta \frac{\rho}{2} c^2 \frac{l}{d_h} \tag{g}$$

The pressure drop can be calculated from the linear fluid velocity (c), the Reynolds number (Re), the fluid density (ρ), the length of the microchannel (l), and the hydraulic diameter (d_h).

The value of ζ for laminar flow is given by Eq. (h) [25]:

$$\zeta = \varphi \frac{64}{Re} \tag{h}$$

The hydraulic diameter is calculated by Eq. (g) from the cross-sectional area A and the wetted perimeter P:

$$d_h = \frac{4A}{P} \tag{i}$$

The value of φ accounts for non-circular cross-section. The value for rectangular cross-sections is a function of the relation of the height and the width of the rectangular. A graphical which relates the relation of the height and the width with the φ-value is given in the literature [25]. The relation of height and width of the rectangular cross-sections of the microchannels in this study is 0.7. This yields an φ-value of 0.91 [25].

Additional pressure drop ($\Delta p'$) is created in the microchannels by a sudden change of the flow cross-section as in the case of the entry and the exit of the microchannel system in this study. The additional pressure drop could be caused by several effects: Eddies might occur within a length of 8–10 times the hydraulic diameter

Table 3

Geometric details of the cross-sections of the mixing chamber and the microchannel system.

Mixer	Number of channels	Cross-section mixing chamber	Cross-section single channel	Cross-section channel system	Ratio of cross-sections (approximately)
z_k10-2foils	20	5×10^{-5} m^2	7×10^{-9} m^2	1.4×10^{-9} m^2	360
z_k10-4foils	40	5×10^{-5} m^2	7×10^{-9} m^2	2.8×10^{-9} m^2	180
z_k10-6foils	60	5×10^{-5} m^2	7×10^{-9} m^2	4.2×10^{-9} m^2	120
z_k10-12foils	120	5×10^{-5} m^2	7×10^{-9} m^2	8.4×10^{-9} m^2	60
z_k10-24foils	240	5×10^{-5} m^2	7×10^{-9} m^2	16.8×10^{-9} m^2	30

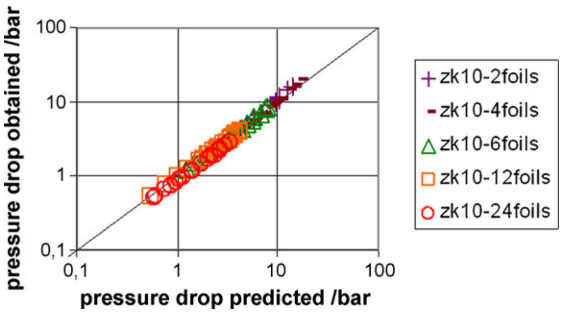

Fig. 10. Parity plot for the pressure drop measurements.

[25]. For the formation of stable laminar profile a length of 0.13Red_h is assumed [25]. Within this length more friction occurs at the wall since the flow has a more uniform distribution over the cross-section. In case the microchannel system is fed over a much larger reservoir with a substantially lower fluid velocity the acceleration needs to be achieved by additional pressure drop. All influences are represented in a value K (Eq. (j)). The value of K is a function of the ratios of the area of the cross-sections of the microchannels and the area of the cross-section of the mixing chamber. A graphical solution relating those ratios with the K-value is given in the literature [25] and yields 1.1 for all mixing devices examined in this study:

$$\Delta p' = K\frac{\rho}{2}c^2 \tag{j}$$

Combining Eqs. (g) through (j) yields Eq. (k):

$$\Delta p_{\text{tot}} = \Delta p + \Delta p' = \frac{\rho}{2}c^2\left(\varphi\frac{64}{Re}\frac{l}{d_h} + K\right) \tag{k}$$

The experimentally determined pressure drops are 20% higher than the theoretical pressure drops predicted by Eq. (k). This discrepancy could be explained with the shrinking of the channel height in the course of diffusion bonding, where high pressures and temperatures are applied to the structured foils. Shrinking of the hydraulic diameter by about 10% results in an increase in the pressure drop of 20% (Eq. (k) notes that a change in the hydraulic diameter also affects the linear velocity and the Reynolds number). Assuming a shrinking of the hydraulic diameter of 10%, the pressure drops can be predicted within an accuracy of ±5% (Fig. 10).

5.2. *Shape of the exit window*

The above given experimental results show that a minimum number of microchannels corresponding with high fluid exit velocities (at cost of high pressure drops in the microchannels) is beneficial for efficient mixing. In order to elucidate a possible influence of the arrangement of the microchannels at the interface between the microchannel system and the mixing chamber (‘shape of the exit window’), four mixer inlays having each 120 microchannels in total were compared. Geometrical details of the mixers compared are reported in Table 4.

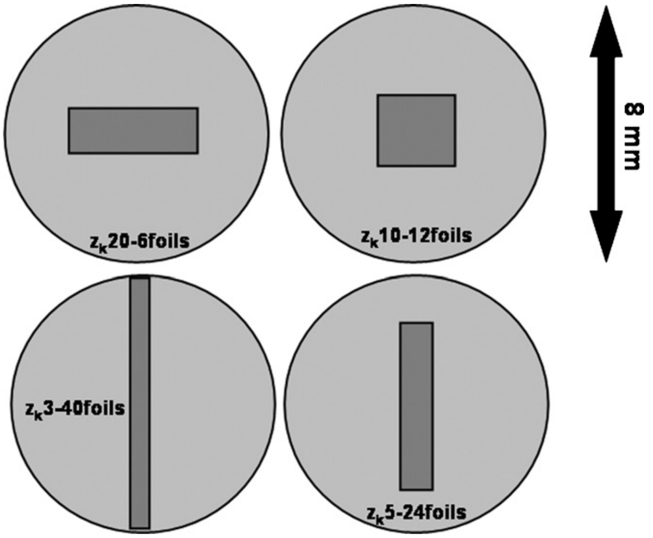

Fig. 11. Sketch of the entry and exit windows of the examined mixers inlays in comparison with the diameter of the mixing chamber.

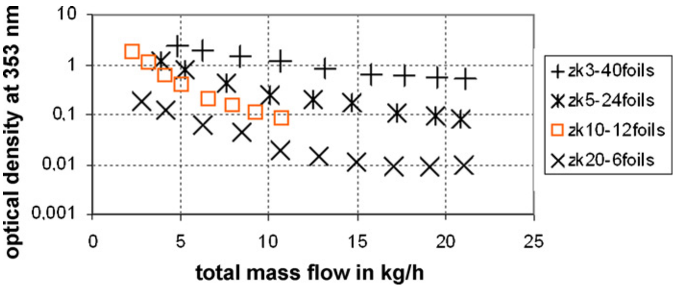

Fig. 12. Experimental characterization of the mixers inlays depicted in Fig. 11.

The dimensions of the channels and fins are identical to the values reported for the previous experiment (Section 5.1.1).

Fig. 11 gives a sketch of the exit windows with the relative size of the mixing chamber and the exit window. The geometry of the entry windows is exactly the same. Since there is only half of the amount of channels for each passage in the entries (which are later combined in the exit window; see Fig. 1) the ‘porosity’ of the ‘entry windows’ is lower.

The experimental characterization of those mixer inlays is represented in Fig. 12.

The shape of the exit window shows a large effect on the experimentally determined optical densities of the resulting mixtures. The wider the exit window, the better the mixing process indicated by the optical densities of the resulting solutions. The taller the exit window, the more triiodide is found in the resulting mixtures indicating less effective mixing processes. It is observed that the logarithm of the optical densities scales linearly with the logarithm of the width of the exit window. Fig. 13 shows the example

Table 4
Geometrical details of the mixer inlays compared.

Mixer inlay	Channels per foils	Number of foils	Fin widths	Width of exit window (theo)	Height of exit window (theo)	‘Contact volume’
z_k3-40foils	3	40	100 μm	0.705 mm	7.87 mm	0.978 mm^3
z_k5-24foils	5	24	100 μm	1.269 mm	4.67 mm	1.880 mm^3
z_k10-12foils = s100-12foils	10	12	100 μm	2.679 mm	2.27 mm	4.073 mm^3
z_k20-6foils	20	6	100 μm	5.499 mm	1.07 mm	8.089 mm^3
s200-12foils	10	12	200 μm	3.948 mm	2.27 mm	7.084 mm^3
s50-12foils	10	12	50 μm	2.679 mm	2.27 mm	4.807 mm^3

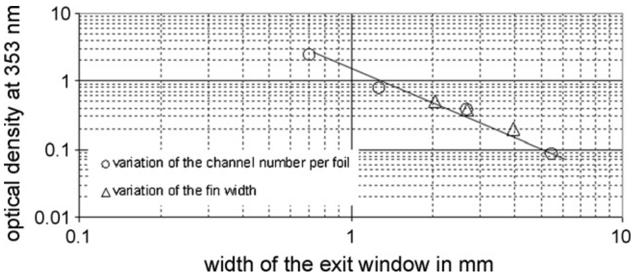

Fig. 13. Optical densities of the resulting solutions as a function of the width of the 'exit windows'.

for a total mass flow throughput of 5 kg/h (circles, variation of the channel number per foil).

With exit windows with a wider width and a smaller height a better contact of the exiting fluids is obtained. This fact is graphically demonstrated in Fig. 2 (two-dimensional graph). For the 'zone of enhanced contact' a volume (of a triangular prism) can be calculated. The values are given in Table 4. With improved contact of the fluids it is more likely that the energy is dissipated in such regions.

5.3. *Variation of the fin width of the microstructured foils*

The above given experimental results (Section 5.2) shed a new light on older experimental findings. Recently [1] the authors reported that bigger fin widths improve the mixing process, indicated by resulting mixtures with lower triiodide concentrations. Three mixer inlays were examined previously. All of them consisted of 12 microstructured foils with 10 micromachined channels per foil. The fin widths were 50, 100, and 200 μm (see Table 4). Bigger fin widths result in bigger widths of the exit windows. Plotting the optical densities of the solutions obtained with those devices (previous study, triangles, variation of the fin width, Fig. 13) achieved at a total mass flow rate of 5 kg/h along with the results obtained from varying the width of the 'exit window' (this study, circles, variation of the fin width) by the number of channels per foil shows that altering the fin widths might be interpreted as another way to alter the width of the 'exit window' of the mixing channels. One mixer was used in both experiments (z_{k}10-12foils = s100-12foils) and is thus double-marked (circle and triangle) in Fig. 13.

6. Conclusions

Among several structural parameters of V-type mixers, which might influence the mixing results three parameters are discussed in this contribution. (1) The number of identical microstructured foils stacked, (2) the 'shape of the exit window', and (3) the fin widths.

In previous studies [1] it was experimentally shown by applying the Iodide Iodate Reaction Method, that V-type mixers can be scaled by varying the number of microstructured foils and keeping the fluid exit velocity constant. In this study we paid particular attention to a possible influence of the top- and bottom foil, which differ on the geometrical environment compared to the 'core foils'. An influence of the 'boundary foils' could not be found in this study. The previous scaling assumptions were substantiated with two new mixer inlays with minimized number of microstructured foils. Energy is dissipated in the mixing chamber due to the abrupt flow area change at the interface of the microchannel system and the mixing chamber. Since for all examined V-type mixers the cross-section of the mixing chamber is by far larger than the combined cross-section of the microchannels, the dissipated energy per mass unit is the same for all devices at a given linear velocity, regardless of the number of foils stacked. Thus the throughput can be scaled by numbering the micromachined foils, keeping constant energy dissipation per mass unit.

On the example of four 120-channel mixer inlays with different measures of the windows of the exiting fluids, it was demonstrated: the wider the width and the smaller the height of the 'exiting window', the better the mixing results, as indicated by low iodine concentrations, when utilizing the Iodide Iodate Reaction Method. Thus a new criterion was identified, which strongly influences the mixing process. Wider 'exit windows' lead to enhanced contact of the exiting fluids to be mixed, in region where energy is dissipated due to a sudden change in cross-section at the interface of the microchannel system and the mixing chamber.

It was previously concluded that larger fin widths are beneficial to the mixing process [1]. In light of the new results mentioned above, the bigger fin widths are interpretated as a gain in width of the fluid exiting windows.

Based on the knowledge developed in previous and the present study simple rules for the optimal design of V-type mixers can be given:

(1) The best mixing results in a V-type mixer are obtained at high exit velocities of the fluids. That means minimizing the number of foils applied for the construction of a V-type mixer for a specific mixing task. Minimizing the number of microstructured foils is restricted in practice by the increasing pressure drops encountered.
(2) Based on the new experimental findings, it is reported that for a given number of micomachined channels, the width of the exit window should be maximized to obtain a maximum 'volume of contact' of the fluids entering the mixing chamber.

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