CHARACTERIZATION OF NANOSECOND MICRO-MIXERS

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Characterization of a four-jet tangential stainless steel micro-mixer

The novel micro-mixer contains four channels (∅ 70 µm) ending in a 'premixing' chamber of 120x120x70 µm (fig. 1).
After the 'premixing' chamber, the fluids enter a small 'mixing' chamber and are mixed within ~ 2 µs (fig. 2). The liquids leave at an orifice (∅ 20 µm) travelling further as a free jet (max. linear jet flow ~ 200 ms-1, dynamic pressure ~ 400 bar) [1].
The mixer is employed to study enzyme reactions in a freeze-quench set up yielding an instrumental dead time of 60 µs, 100 fold shorter than any other device.

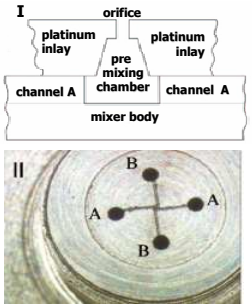

Fig. 1: (I) Geometry of the mixer; (II) Channels and the premixing chamber of dismounted mixer

Mixing efficiency

To characterize the mixing efficiency of the micro-mixer, the fluorescence quenching of o-hydroxycinnamic acid, HCA was monitored in a jet (fig. 2).

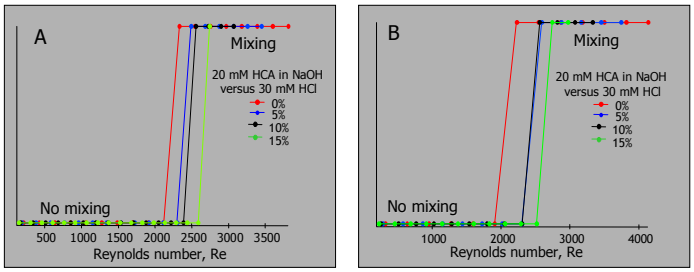

Fig. 2: Mixing at various concentrations of glycerol. The mixing was followed by the quenching of HCA(alk) vs HCl, (A) 1:1 flow rate ratio: HCA(alk) vs HCl; (B) 2:1 flow rate ratio: HCA(alk) vs HCl.

For a 1:1 and 2:1 flow rate ratio between HCA(alk) and HCl mixing occurs in a transient regime at Re > 2300 and Re > 2200, respectively. With increasing glycerol concentrations in both solutions, the Re stays the same ~ 2600, in agreement with turbulent mixing theory.

Characterization of four-jet tangential glass-silicon micro-mixer chips

To determine where mixing occurs, in the 'premixing' or in the 'mixing' chamber a few generations of novel chips for optical studies are designed (fig. 3). The opposite channels etched in 360 µm thick Si are offset with respect to each other by ½ width of the channel. The channels are covered by 1.1 mm thick glass. The orifice is in the Si part of the mixer (Ø 25 µm – 70 µm), providing a mixing volume of the small chamber between 16-127 pL.

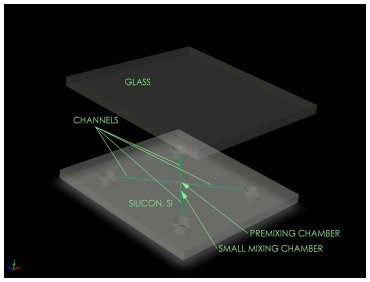

Fig. 3: Glass-silicon four-jet micro-mixer chip

To determine the percentage of premixing in the micro-mixers, fluorescence appearance during deprotonation of 8-hydroxypyrene 1,3,6-trisulfonic acid, trisodium salt, HPTS was monitored in the premixing chamber using a fluorescence microscope. When NaOH was 1.5, 10 or 30 fold in excess over HCl, it was determined that 6, 14 or 16.5% / 2.5, 8.8 or 11.4% / 2.5, 10 or 13.5% and 2, 8.3 or 10% of premixing occurred in the premixing chamber of the chips with 70/50/30 and 25 µm orifice diameter, respectively (fig. 4 and fig. 5).

[1] A. Cherepanov and S. de Vries. *BBA*, 1656, 1-31, **2004**.
[2] F. Wiertz, *et al. FEBS Letters*, 575, 127-130, **2004**.

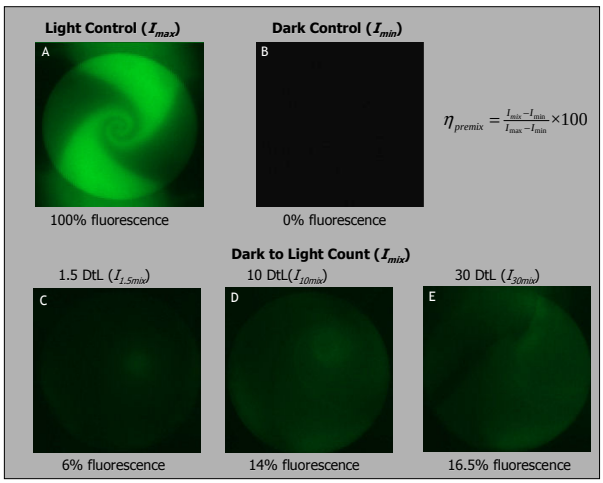

Fig. 4: Fluorescence appearance of HPTS dye in the 'premixing' chamber of the chip with 70 µm orifice diameter and at the flow rate of 10 mL.min^{-1}: (A) HPTS(alk) in NaCl vs NaOH in NaCl -> light control; (B) HPTS(ac) in NaCl vs HCl in NaCl -> dark control; (C, D, E) HPTS(alk) in NaCl vs HCl in NaCl when NaOH is 1.5; 10 and 30 fold in excess over HCl, respectively -> dark to light count - percentage of premixing in the premixing chamber

Values of calculated Re in the mixing chamber for the chips (Ø 25 µm-70 µm), (Re >> 2000 transient/turbulent flow) are respectively, 1.9/2.7/4.5 and 5.4 fold larger than their values of Re in the premixing chamber, (Re < 2000, laminar flow).
Since at Re < 2200 no mixing occurs, all (> 85%) of the mixing must occur in the small chamber. The calculated mixing time is 760/560/310 and 360 ns for the chips with 70/50/30 and 25 µm orifice diameter, respectively.

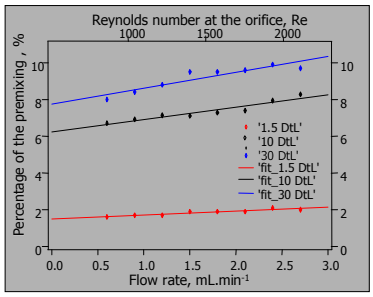

Fig. 5. Percentage of premixing in the premixing chamber during deprotonation of HPTS when NaOH was 1.5; 10 or 30 fold in excess over HPTS in HCl as a function of the flow rate in the system and calculated values of the Re at the orifice at each flow rate for the chips with 25 µm orifice diameter.

Conclusion

The time of mixing can be even shorter ~ 200 ns if the same experiment would be successfully done with the (Ø 20 µm) chip, as in the stainless steel mixer. This mixer would then be 100 fold faster than any described in the literature.

Outlook

For optical studies a glass cylinder will be used in stead of a free jet. The cylinder (25-50 mm diameter path length) is positioned under an inverted florescence microscope, connected to a monochromator and a Hg light source with collimating optics.
Using both mixing systems, the time course of chemical and enzymatic reactions, applying UV-Vis absorbance and fluorescence spectroscopy will be studied with a time resolution in the nanoseconds.