RHEOPLUG –
SEGMENTED FLOW BASED VISCOMETER

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ABSTRACT

We present a novel method to measure the viscosity of liquid mixtures in µL-volume plugs based on a segmented flow platform [1]. Therefore, up to three different liquids of different viscosities are injected into a common plug which is afterwards transported through an air filled channel by a 15-20 mbar vacuum below ambient pressure at the chip outlet. Rapid mixing within the plugs is enabled by internal advection and the plug velocity directly depends on the viscosity of the plug. Following this approach, the viscosities of water/PEG mixtures in the range of 1-68 mPa s could be successfully measured on-chip.

KEYWORDS: Segmented Flow, Viscometer, Liquid Plug, Mixing, Injection

INTRODUCTION

The segmented flow platform based on the flow of immiscible fluids in microfluidic channels offers a wide range of applications for injecting and mixing different reagents in droplets or plugs surrounded by a carrier fluid. Due to this separating phase the often problematic dispersion, well known during transportation along microfluidic channels, is confined to the volume of the droplets [1]. The sharp phase interface between plugs and carrier phase also enables a precise observation of the plug movement and a determination of velocities. Within this work we use the velocity dependency on viscosity to implement a microfluidic segmented flow based viscometer for different aqueous plugs utilizing air as carrier phase.

FUNCTIONAL PRINCIPLE

Figure 1 shows the principle of the segmented flow based viscometer *RheoPlug*. The formation of a common plug is accomplished by high precision syringe pumps, injecting the liquids into the gas filled channel (Fig. 2). An additional inlet optionally enables the injection of another liquid into the existing plug further downstream, e.g. to initiate a (bio-)chemical reaction.

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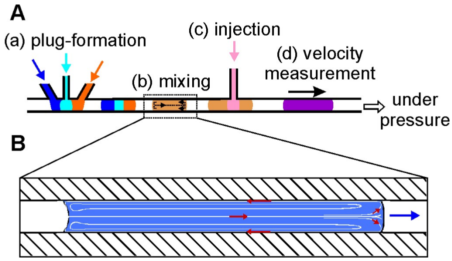

Figure 1. RheoPlug principle. Up to three liquids form a common liquid plug (a), and are afterwards mixed (b) during the pressure driven transport along the gas filled channel (bottom: CFD-simulation of plug internal mixing). At a downstream position, a fourth liquid can be optionally injected into the plug (c).

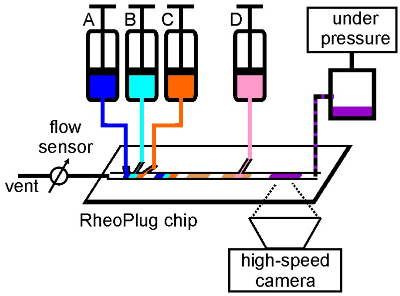

Figure 2. Measurement setup. Different liquids A-D are injected into the microchannels, using high precision syringe pumps. For the transport of the plugs, a light vacuum is applied at the channel outlet, while a flow sensor measures the inflowing gas at the vented inlet.

The plug is transported using a slight vacuum at the chip outlet. Following the law of *Hagen-Poiseuille* in laminar flow – and assuming long plugs in small cross-sectional channels – the viscosity of the liquid plug η_{plug} is inverse proportional to its velocity u_{plug} ($\eta_{plug} \sim u_{plug}^{-1}$). Thus, the plug-viscosity can be either determined optically (high-speed camera) or by measuring the gas flow rate I_V at the vented inlet (since $u_{plug} \sim I_V$). Using gas as separation phase leads to an increased sensitivity and enables the usage of a reusable flow sensor which is not in direct contact to the liquids. This is an advantage compared to methods based on oil as separation phase [2].

EXPERIMENTAL RESULTS

The chips are fabricated by soft embossing in COC (cyclic-olefin-copolymer) [3] and subsequent sealing by solvent bonding of a 140 µm thick COC foil.

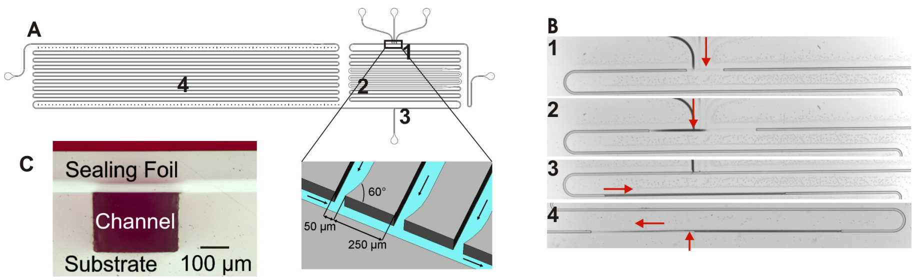

***Figure 3.** The chip features four main parts (A): 1. plug formation zone; 2. mixing channel; 3. injection channel; and 4. meandering measurement channel. (B): optical photographs show the plug formation of two liquids (transparent and ink-colored water) and the subsequent good mixing result after the first channel bend (B3), before another liquid is injected at a downstream position (transparent water, B4). A typical channel cross section of a solvent bonded COC-chip is shown in (C).*

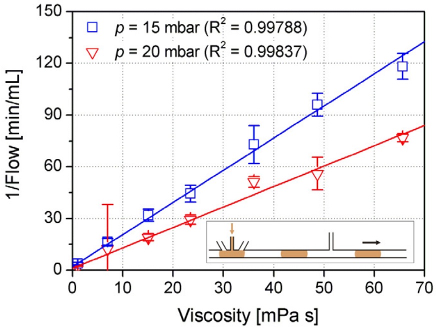

Figure 4. *Viscosity measurement of pre-mixed water / PEG mixtures. As expected, the reciprocal gas flow rate measured by the flow sensor is proportional to the viscosity of the liquid within the plug (reference measurement on rotating plate viscometer).*

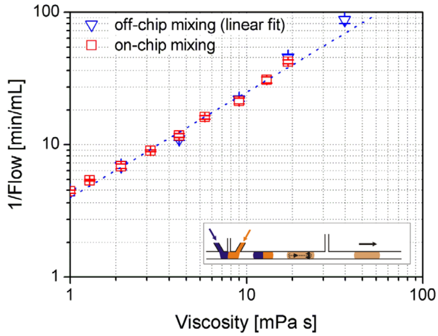

Figure 5. *On-chip generation of water / PEG mixtures and subsequent viscosity measurement. The results prove the quality of the integrated processes: metering (volume of injected liquids into the plug) and mixing on the RheoPlug platform.*

Figure 3 shows a typical channel cross-section and a picture series visualizing the plug formation, mixing and injection process. Viscosity measurements with off-chip prepared water/PEG mixtures are shown in Figure 4. They are in good correlation to reference values measured on a rotating plate viscometer. The strength of the *RheoPlug* viscometer is the integrated processing of several liquids, i.e. metering, mixing and viscosity determination. This is successfully demonstrated by additional on-chip measurements leading to the same results as the off-chip mixing experiments (see Fig. 5). For both measurement series, a microfluidic channel of cross-section 200 x 300 µm² has been used. Typical plug volumes and velocities are in the range of 1-2 µL and 2-50 mm/s, respectively.

CONCLUSIONS AND OUTLOOK

Automated and integrated viscosity measurements of minute liquid mixture amounts have been shown as a new application on the segmented flow platform. Future work will focus on the continuous online measurement of blood coagulation on the *RheoPlug* platform by injecting an activating chemical into a minute amount of blood containing plug and the subsequent monitoring of viscosity changes.

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