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Direct velocity imaging by magnetic resonance in a static mixer model produced using stereo lithography

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HIGHLIGHTS

- Three-dimensional velocity field is measured in static mixers using MRI velocimetry.
- Non-Newtonian and Newtonian fluids are examined in static mixers.
- An SMX type static mixer is produced using stereo lithography.

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ABSTRACT

An MRI-compatible, minimally scaled model of an SMX-type static mixer was produced of an acrylic photopolymer using stereo lithography. This mixer was mounted into a flow cell which was inserted into a vertically oriented MRI system operating at 200 MHz. Water and shear-thinning Xanthan gum solutions at various concentrations were circulated through the mixer and flow velocity imaging experiments for all three spatial directions were performed at several flow rates. The resulting flow velocity images show a more spatially focussed flow pattern for the Xanthan solutions than for plain water. Various analyses of the resulting flow velocity distributions were carried out for the experimental data, focused on finding dead zones within the mixing geometry that might cause clogging when polymer solutions are led through during reaction process.

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1. Introduction

The performance of statical mixers has been intensively studied by many research groups. The majority of investigations have been focused on mixing quality and pressure drop across the static mixers. Most studies on mixing quality were done by analyzing samples taken at the outlet of the mixer. Tozzi et al. (2013) used magnetic resonance imaging to observe the change in concentration along the axis of a spilt and combine static mixer. Avalosse and Crochet (1997) photographed various frozen cross-sectional areas in a Kenics mixer to compare the actual mixing quality with results of finite element simulations. Intensive investigations of the mixing process via CFD have been undertaken (Lindenberg and Mazzotti, 2009; Hobbs et al., 1998; Byrde and Sawley, 1999). Due to scarcity of velocity data usual validation parameters for the simulation results were limited to pressure drop and mixing quality. Only very little work was done to observe fluid velocity inside the mixers. Kumar et al. (2008) used a three-hole probe to measure air speed in a Kenics mixer, Jilisen et al. (2013) measured 3 dimensional velocity profiles in a Kenics geometry by using particle tracking velocimetry. These methods need either the introduction of a probe disturbing the flow field within the mixer or optical access to the fluid and introduction of special particles that allow optical observation. Blümler et al. (1998) published a study with flow measurements using magnetic resonance velocity measurement for a Kenics type mixer. Measurements were done with Newtonian fluids. A method for tracing the position of two immiscible fluids was shown. A large range of flow MRI work on purpose-built plastic models was done in the context of percolation studies (Müller et al., 1995). Those models were produced by a layer-by layer lamination method in which the layers were subtractively structured. Later, also models produced by various microfabrication techniques were applied in similar studies (Kossel and Kimmich, 2005). Besides flow driven by a pressure

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† This paper is dedicated to the memory of Heike Herold who passed away on March 9th 2015 after a short, serious illness. A mechanical engineer by training, she had spent a few years focussed on raising her kids before joining us as a PhD student in 2010. She was a great person to work with - a competent and determined worker on her project and a friendly and mature personality. She had planned to submit her thesis covering various aspects of flow NMR chemical engineering applications later this year.

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gradient, also thermally driven convection (Weber et al., 2001) and electrically driven flows (Buhai and Kimmich, 2006) were studied in such model geometries. Furthermore, many groups have studied flow velocity distributions in bead packs and similar porous systems (Bencsik et al., 1998; Sederman et al., 1998). A rather new development in this field is the determination of dispersion properties that allow the direct assessment of the quality of the mixing process as well as studies of the impact of fouling on the flow pattern inside the porous medium (Fridjonsson et al., 2014).

Along with their major application for mixing two or more different materials, static mixers are also used for homogenisation of melts and concentrated solutions in polymer processing and polymerisation reactions (Thakur et al., 2003). In the latter case media clogging of mixers may occur if polymerisation processes in stagnant regions form nonflowable by-products. For such application exact knowledge of flow inside the mixer is of major interest. In this work the flow distribution in a SMX type mixer was investigated using magnetic resonance imaging. A Newtonian and a shear thinning liquid were investigated to study the different velocity fields. Special care was taken to identify volumes with low flow velocity. This provides basic knowledge for further optimisation of mixer geometry to reduce the probability of clogging in the device.

2. Experimental

Nuclear magnetic resonance measurements provide different methods for velocity measurements. In the SMX type mixer under investigation a 'time of flight' or 'tagging' method would be disadvantageous as there is very limited access to 3 dimensional velocity data. Phase encoding methods provide a three-dimensional velocity picture for a 3 dimensional structure. Theory of three-dimensional velocity measurements is intensely discussed (Müller et al., 1995; Kossel and Kimmich, 2005; Weber et al., 2001; Buhai and Kimmich, 2006; Bencsik et al., 1998; Sederman et al., 1998; Fridjonsson et al., 2014; Thakur et al., 2003; Hardy, 2012; Bümich, 2005; Caprihan and Fukushima, 1991; Callaghan, 1991; Weis et al., 1996).

Velocity measurements were performed in a Bruker Avance 200 SWB tomograph (Bruker GmbH, Rheinstetten, Germany) using the Bruker routine m_flowpc within the BRUKER software ParaVision (Version 3.0.2. pl1). Three-dimensional velocity readings were taken in 21 slices that were oriented parallel to the main flow direction. The slice thickness was 1 mm. The image plane was 25 mm × 25 mm with a 128 × 128 points data matrix. The field of flow was set to 80 mm/s, recycle delay 1.75 s and 1.1 s for water and Xanthan solution respectively. For each image 8 scans were averaged. Echo time was set to 11.589 ms. The already Fourier transformed and pre-processed data were further processed using Matlab® 7.9.0 (the MathWorks Inc., Natick, MA, USA).

For better differentiation between solid mixer geometry and areas of close to zero velocity, a 3 dimensional image of the mixer geometry was taken in the same tomograph using the BRUKER routine m_rare for a 25 × 25 × 25 frame setting 256 × 256 × 256 reading points in each direction. The pre-processed data were further processed into a surface reconstruction using Matlab® (Fig. 1) and these values were used when analysing the flow data in Matlab®.

The liquids used in this study were demineralised water and Xanthan (Spinnrad GmbH, Bad Segeberg, Germany)–demineralised-water-solution 0.2% and 0.4% weight concentration. To all liquids 1 mmol/l Gadovist (Schering Deutschland GmbH, Berlin, Germany) was added to reduce the longitudinal relaxation time and thus allow faster signal accumulation. At these concentrations of the contrast agent no influence on the viscosity of the mixtures is expected. The viscosity functions of the Xanthan solutions were measured at 20 °C using a Mars viscosimeter (Thermo Fischer Scientific Inc., Waltham, USA) with Z20DIN geometry (Fig. 2).

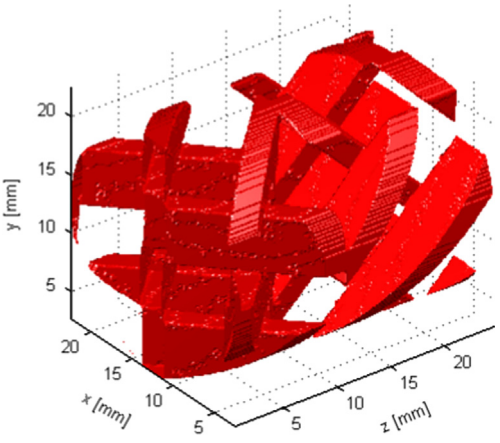

Fig. 1. Surface reconstruction of mixer geometry.

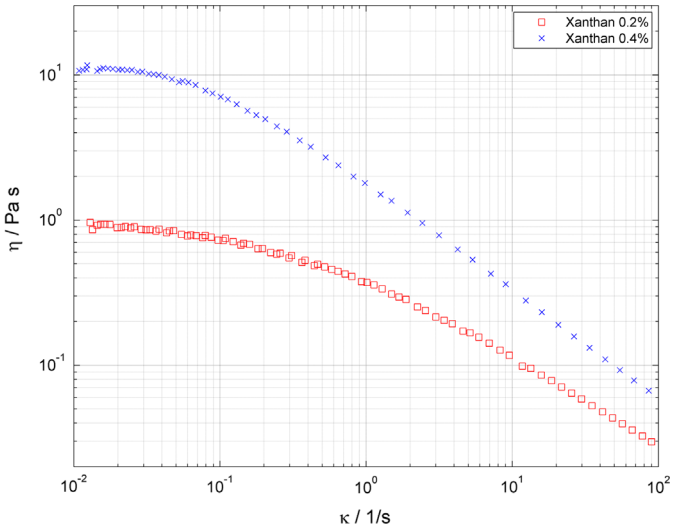

Fig. 2. Viscosity readings for Xanthan 0.2% and 0.4% solutions prior to test.

Table 1
Liquids and volumetric flow rate under investigation.

Liquid	Average volumetric flow rate (ml/s)		
	1	2	2.7
Water	–	×	–
Xanthan 0.2%	×	×	×
Xanthan 0.4%	×	×	–

Flow was produced using a 3RD12 dispenser pump (ViscoTec, Töging am Inn, Germany); flow rates between 1 ml/s and 2.7 ml/s have been used for the study (see Table 1).

The mixing geometry was produced from Somos® WaterShed XC 11122 (DSM Functional Materials, Hoek van Holland, Netherlands) using stereo lithography on a Raplas RPS 450 (Raplas, Jena, Germany). It was introduced into a 20 × 24 × 515 mm polycarbonate tube, which provided connectors to hoses on both sides. One connector was removable, so the outer measurement cell can be used for measurements on different mixer geometries. The total length of the mixing geometry is 483 mm. It consists of 23 compartments each 21 mm long. Velocity measurements were taken in the area of 18th and 19th compartment including about half of each compartment. In this area the effects of inlet design are insignificant.

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