BLENDING OF NON-NEWTONIAN FLUIDS IN STATIC MIXERS: ASSESSMENT VIA OPTICAL METHODS.

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Abstract

The performance of KM static mixers has been assessed for the blending of Newtonian and time-independent non-Newtonian fluids using planar laser induced fluorescence (PLIF). A stream of dye is injected at the mixer inlet and the distribution of dye at the mixer outlet is analyzed from images obtained across the pipe cross section. The effect of superficial velocity, scale of static mixer, flow ratio between a primary and a secondary injected flow and finally the injection position, are investigated to determine the consequences on mixing performance. Different methods are discussed to characterize mixing performance, comparing CoV and maximum striation thickness. Conflicting trends are revealed in some experiments results, leading to the development of an areal based distribution of mixing intensity and a distribution of striation with high mixing intensity. For two-fluids blending, the addition of a high viscosity stream into the lower viscosity main flow causes very poor mixing performance, with unmixed spots of more viscous component observable in the PLIF image. The final part of the work is focused on a preliminary understanding of advective mechanisms such as shearing of non-Newtonian fluid drops and stretching of a non-

Newtonian fluid filaments.

Background

Laminar mixing using static mixers has been the subject of much interest in the last few decades. From an industrial perspective, static mixers provide the opportunity to progress towards reductions in inventory and plant footprint, whilst for academia, the research field is ongoing, particularly for the blending of fluids with complex rheology. From a practical point of view, the development of knowledge of laminar mixing in such devices is essential in order to ensure a similar or an improved process performance compared with traditional batch processes (e.g. stirred vessels).

Additional advantages of continuous processes include the reduction of utility costs and improved process flexibility allowing rapid product changeover, with the caveat that improved process control measures will be required to ensure consistent product quality. Many studies have been carried out on this subject with particular emphasis on heat and mass transfer characteristics. For example, Joshi et al. (1995) compared the performance of static mixers with open tube designs in order to verify performance improvements in terms of heat transfer enhancement in laminar flow.

The choice of static mixer design for a given process duty is a moot point; the optimisation of geometry is a major challenge in pipe mixing with laminar flows, due to the absence of an advective radial mixing mechanism since all fluid streamlines are in the axial direction. Many works in the literature deal with the comparison of different commercial static mixers in the laminar flow regime, such as the Kenics (KM) and SMX mixer designs which are the focus of this thesis. In the work of Rauline *et al.* (2000) the performances of these different geometries of static mixer are compared using 3D numerical simulations. Several criteria are chosen as the basis for the performance evaluation, namely, pressure drop per unit length, the number of mixer elements, the Lyapunov exponent, the mean shear rate and the intensity of segregation. The main purpose of laminar mixing studies is to gain understanding of the physical principles in order to develop meaningful theory. This topic has evolved mainly from empiricism to a semi qualitative level, via experimental and modelling methodologies. Laminar mixing is applicable in many different industrial applications including food (Talansier *et al.*, 2013), personal care, household products, slurries, polymer manufacture and, finally, catalyst washcoats. All of these products have a non-Newtonian rheology, as indeed do most fluids processed by industry; this entails an additional complication in understanding mixing performance. The literature on static mixers has generally concentrated on the blending of Newtonian fluids (Zalc *et al.*, 2002) or on providing performance for the blending of non-Newtonian fluids based upon bulk fluid flow or pressure drop measurements (Meijer et al., 2012, Kumar *et al.*,, 2008, Chandra *et al.*, 1992, Ishikawa *et al.*, 1996). No literature exists on the local mixing conditions as a function of the blending of single, or multiple fluids with non-Newtonian rheology, yet in the context of foods and polymers, this is key data. Liquid mixing applications are frequently carried out at low velocities or involve high viscosity substances or liquids with complex rheology which drastically increase the pressure drop of the system.

However, in most of the works where mixing performance is discussed, the characterisation is usually based upon statistical approaches such as the coefficient of variation or maximum striation size. These two methods have been discussed at length and sometimes criticised in the literature (Kukukova *et al.*, 2009) in particular when a complex mixing pattern has to be characterised. These methods, if used in isolation, can create misleading results. The need for a combined method which allows the characterisation of scale and intensity of mixing leads to the main objective of this thesis. Mixing performances for the blending of non-Newtonian fluids using static mixers will be presented showing the characterisation of mixing following the previous methods (coefficient of variation and maximum striation thickness) and the proposed combined method.

Key innovations of the thesis work

The overall aim of this thesis is the development of a new approach to define mixing performance for inline mixing using mainly non-Newtonian fluids. The methods developed are generic in nature and can be applied to a wide range of mixing processes where information about mixing pattern is required, nevertheless the focus of this thesis is on blending in static mixers which provide a mechanism to benchmark the approaches developed. The core of this new method is the analysis of mixing patterns obtained using the Planar Laser Induced Fluorescence (PLIF) technique. PLIF analyses are carried out in the laminar mixing regime with the use of Non-Newtonian fluids.

The methods have been developed according to the specific objectives of the study which are given below:

- Development of a new method to characterise mixing performance using an areal distribution of mixing intensity to describe blending of non-Newtonian fluids in Kenics static mixer.
- Comparison of the new analysis methods with conventional mixing parameters which represent the scale and intensity of segregation.
- Development of a new analysis to characterise scale of segregation more deeply based on previous developed method.
- Study of the effect of system and fluid parameters as flow rate, flow ratio, size of static mixer, different injection and different injection position upon the blending of

Non-Newtonian fluids in a KM static mixer. Different experiments are carried out and compared for the understanding of the behaviour of shear thinning fluids upon different conditions.

- Comparison of the behaviour of different static mixers at the same inlet conditions, in terms of performance and energy consumed, focussing on KM and SMX Plus designs (limited access due to confidentiality agreement).

These analyses presented enable the efficiency of different static mixers to be determined: how the behaviour of Non-Newtonian fluids affects the mixing performance is a key objective of this thesis to enable determination of the optimal mixing conditions for a given duty. The final aim of the thesis is to obtain understanding of the individual phenomena causing mixing by advection within static mixers. Preliminary studies have been made which aim to obtain understanding of how the disruption of single fluid filaments under the action of shear or elongational stresses leads to an increase in interfacial area. This part of work has been focussed on filament stretching and drop stretching of non-Newtonian fluids. These simplified systems have been investigated to obtain new information about the advective mechanisms for the blending of non-Newtonian fluids.

Achievements of thesis work

This section summarises the main conclusions achieved with this thesis work.

Development of a new method to characterise mixing performance using an areal distribution of mixing intensity to describe blending of non-Newtonian fluids in Kenics static mixer and comparison of the new analysis methods with conventional mixing parameters which represent the scale and intensity of segregation.

The primary objective of this thesis was to investigate how to determine the mixing performance using static mixer in laminar flow. In most of the previous studies for the quantification of mixing intensity, coefficient of variation was the most often used parameter to determine the level of mixedness. Statistically averaged values based on concentration distribution and empirical correlations based on length and diameter of static mixer, were used as methodology to evaluate the coefficient of variation. To the best of current knowledge, for the quantification of scale of segregation, striation thickness is the most used method to evaluate the mixing performance. This thesis has debated the importance of considering both aspects in tandem for correct interpretation of the mixing performance; considering only a single measure is a known problem in the literature (Kukukova et al., 2009, Kukukova et al., 2011). This issue has been addressed in the methods and analysis presented. Analysis of PLIF images has been performed to determine the mixing performance of KM static mixers using Newtonian and non-Newtonian aqueous solutions as a function of number of elements and viscosity ratio of the two fluids. A method has been developed which considers the distribution of the cross sectional area with a given intensity of mixing, this areal analysis combines both intensity, in terms of log-variance, and scale, in terms of the fraction of the cross section with a given intensity. The method shows promise for the evaluation of mixing performance and can be considered as an addition to conventional approaches.

- *Development of a new analysis to characterise scale of segregation more deeply based on previous developed method.*

The developed method allows the identification of striations of similar intensity. Analysis of striation area distribution is presented to schematize individual contiguous striations as a function of a non-dimensional area versus a non-dimensional length. This new method shows the complexity of information-rich PLIF images, and allows the classification of different experiments where CoV and striation thickness alone failed to clearly distinguish the effects of different parameters. The methods developed have different industrial relevance as each method characterizes a different aspect of the mixing. For example, when an overview of the process is needed, the area fraction method can be used to estimate the amount of “lump” that has to be minimized in a downstream processing. But in a reactive system where the interface area is important, the striation method distribution can give an estimation of total interface length of the analysed cross section which is key aspect to take in account to determine the performance of the system.

- *Study of the effect of system and fluid parameters as flow rate, flow ratio, size of static mixer, different injection and different injection position upon the blending of Non-Newtonian fluids in a KM static mixer. Different experiments are carried out and compared for the understanding of the behaviour of shear thinning fluids upon different conditions.*

Analysis of PLIF images has been performed to determine the mixing performance of KM static mixers using non-Newtonian aqueous solutions as a function of velocity, scale, flow ratio and injection position and comparing the effect of these parameters to the viscosity ratio of the two fluids (main flow: always fluid 1, injected fluid: fluid 1 and 2). The identification of areas in the pipe cross-section with a given range of log-variance enables identification of regions where the mixing is performed down to the micro-scale, but also unmixed or poorly mixed regions in the flow. The analysis of PLIF images allowed the detection of viscous stream filaments evident as spots when a fluid of higher viscosity was injected into a lower viscosity continuous phase, which is not predictable using conventional design approaches. This new method shows promise in unravelling the complexity of information-rich PLIF images, beyond a sole number-based mixing criterion. As velocity increases the effect of varying the viscosity ratio becomes less important, whilst increasing the size of the static mixer decreases the mixing intensity performance since energy inputted per unit mass decreases, at constant velocity. Scale has the greatest effect on the size of striations with poor mixing evident. However when the data is presented in terms of energy consumed per unit mass, the 1” size is more efficient due to possessing a lower pressure drop per unit length. Increasing the flow ratio between the injection and the main flow increases the overall mixing performance. The wall injection for the mixing of non-Newtonian fluids is not a suggested operating configuration as it negatively affects the overall mixing performance.

Publications arising from this thesis

The following articles have been published or presented as part of this research

Conferences

<u>Conference publications:</u>

Alberini, F., M. J. H. Simmons, et al. (2011). Mixing of time-independent non-Newtonian fluids in a Kenics static mixer using an optical method for intensity and scale of segregation. Oral presentation at International Symposium on Mixing in Industrial Processes VII (BEIJING 2011)

Alberini, F., M. J. H. Simmons, et al. (2012). A single mixing criterion to identify mixing performance based on a combination of scale and intensity segregation in static mixers using non-Newtonian fluids. Oral presentation IChemE research student competition on fluid mixing processes (London 2012)

Alberini, F., M. J. H. Simmons, et al. (2012). Mixing of time-independent non-Newtonian fluids using static mixers. Oral presentation and poster competition JM student conference (Loughborough 2012)

Alberini, F., M. J. H. Simmons, et al. (2012). Mixing Patterns in KM Static Mixers using Non-newtonian Fluids: Effect of Scale, Viscosity Ratio and Flow Rate. Oral presentation at NAMF Mixing 23 (Mayan Riviera, Mexico 2012)

Alberini, F., M. J. H. Simmons, et al. (2012). A combined criterion to identify mixing performance for the blending of non-Newtonian fluids using a Kenics static mixer. Poster presentation at 14th European conference on mixing (Warsaw, Poland 2012)

Alberini, F., M. J. H. Simmons, et al. (2013). Study of the blending of non-Newtonian fluids in static mixer using PLIF. Oral presentation and poster competition JM student conference (Loughborough 2013)

Alberini, F., M. J. H. Simmons, et al. (2014). Area distribution and individual striation methods to identify mixing performance via an optical method (PLIF) for the blending of non-Newtonian fluids in static mixer. Oral presentation at NAMF Mixing 24 (Sagamore Resort, Lake George, NY, US 2014)

Alberini, F., M. J. H. Simmons, et al. (2014). Analysis of Mixing Performance using Planar Laser Induced Fluorescence for the Blending of Shear-thinning Fluids in Static Mixers. Oral presentation at International Symposium on Mixing in Industrial Processes VIII (Melbourne 2014)

Journal papers

ALBERINI F., M.J.H. SIMMONS, A. INGRAM, E.H. STITT. Use of an areal distribution of mixing intensity to describe blending of non-Newtonian fluids in a Kenics KM static mixer using PLIF. AIChe journal (accepted) (2014)

ALBERINI F., M.J.H. SIMMONS, A. INGRAM, E.H. STITT. Effect of system and fluid parameters upon the blending of shear-thinning fluids in a KM static mixer. Chemical Engineering Science journal (submitted) (2014)

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