



Turbulent liquid–liquid dispersion in SMV static mixer at high dispersed phase concentration

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ABSTRACT

The aim of this paper is to investigate the influence of physico-chemical parameters on liquid–liquid dispersion at high dispersed phase concentration in Sulzer SMVTM mixer. Four different oil-in-water systems involving two different surfactants are used in order to evaluate the effect of interfacial tension, densities and viscosities ratio on mean droplets size diameters. Moreover the influence of the dispersed phase concentration on the pressure drop as well as on the droplet size distribution is investigated. Two different droplets size distribution analysis techniques are used in order to compare the resulting Sauter mean diameters. The comparison between residence time in the mixer and surfactants adsorption kinetics leads to take into account the evolution of the interfacial tension between both phases at short times. Finally experimental results are correlated as a function of dimensionless Reynolds and Weber numbers.

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1. Introduction

Liquid–liquid dispersions are often found in the process industry. They can take part to processes like liquid–liquid extraction, or reactions involving an emulsification step. They can also constitute consumable products such as in the food, cosmetic or drug industry. In both cases it is important to control the droplet size distribution and the mean diameter that could determine the final properties of the product.

Static mixers consist of a series of identical motionless elements inserted in a pipe, column or reactor. They redistribute the fluid in directions transverse to the main flow. The only energy cost depends on the power required for pumping. Generally, static mixers offer small space requirement, low equipment cost, short residence time and few maintenance constraints compared to other equipments. Even if they can be incorporated in pump-around loops in batch or semi-batch processes, this kind of device is naturally well adapted for continuous processes.

There is a wide variety of static mixers that are optimized for specific applications. Different designs are proposed depending on the flow regime and the applications. In their review Thakur et al. (2003) listed the principal commercial static mixer designs and their

different industrial applications including mixing of miscible fluids, thermal transfer and homogenization, and interface generation between two immiscible phases.

In the literature liquid–liquid dispersion in turbulent flows has been studied by many authors with different static mixer designs. The main encountered designs are the Kenics mixer (Middleman, 1974; Berkman and Calabrese, 1988; Lemenand et al., 2001, 2003, 2005; Yamamoto et al., 2007) and the SMXTM Sulzer mixer (Streiff, 1977; Streiff et al., 1997; Hirschberg et al., 2009; Theron et al., 2010; Theron and Le Sauze, 2011). Other mixers can be encountered but they are less documented and their use remains uncommon.

Most of the publications deal with dispersed phase concentrations lower than 0.25 (Middleman, 1974; Streiff, 1977; Matsumura et al., 1981; Al Taweel and Walker, 1983; Berkman and Calabrese, 1988; Al Taweel and Chen, 1996; Streiff et al., 1997; Legrand et al., 2001; Lemenand et al., 2001, 2003, 2005; Hirschberg et al., 2009; Theron et al., 2010). The effect of the dispersed phase ratio is never clearly studied except by Yamamoto et al. (2007) who worked on water-in-oil emulsions with a dispersed phase concentration ranging from 0.02 to 0.74, and did not point out an effect of the dispersed phase concentration on the droplets size distribution.

Nowadays, the need to control continuous or batch processes has become more and more important. That is why on-line analysis measurements have been developed in addition to classical off-line ones. Among the parameters requiring controlling the mean droplets size measurement can be cited. The different techniques are based on optical visualisation, laser diffraction or

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acoustic principles. The technique can be chosen according to the physical properties of the system, the complexity of installation and the expected results.

The advantages and drawbacks of the on-line droplet size analysis techniques are detailed in Table 1.

The SMVTM static mixer has been created in 1970 by the Sulzer Company. It consists of a stack of corrugated plates with a “V” shape. It is well known to perform gas–liquid and liquid–liquid dispersion for mass transfer, reaction or mixing and homogenisation of gas or liquid of low viscosity in turbulent flow. Curiously there is a lack of available information about liquid–liquid dispersion in Sulzer SMV static mixer. The only authors who reported emulsification’s experiments in this type of mixers are Streiff (1977) and Streiff et al. (1997). Thus, the aim of this paper is to investigate the ability of this mixer to perform turbulent liquid–liquid dispersion, and especially at high dispersed phase concentration ($\Phi=0.25$ – 0.60 in volume).

Four Water/Surfactant/Oil systems are chosen. The first part of this study deals with analysing the stability of emulsions obtained, and with comparing droplet size distributions obtained with two different techniques. These techniques are a classical off-line one based on laser diffraction and an on-line measurement based on light backscattering. Then the pressure drop is quantified for high Reynolds numbers for the different liquid–liquid systems, at same dispersed

phase concentration. For the Water/PVA/Toluene system, the effect of the dispersed phase concentration on the pressure drop is evaluated. The effects of different parameters (dispersed phase concentration Φ , flowrate and physico-chemical parameters) on the droplet size distribution are examined. Then the results are correlated in terms of Sauter mean diameter d_{32} as a function of the mean energy dissipation rate and as a function of dimensionless numbers taking into account hydrodynamic and physico-chemical parameters.

The residence time in the static mixer is really short compared to the adsorption kinetics of the surfactants used to stabilize the droplets interface and to reach lower droplets sizes. A special attention is paid to the evolution of the interfacial tension value at short times.

2. Materials and methods

2.1. Fluids

Four different Water/Surfactant/Oil systems are used in order to evaluate the influence of physico-chemical parameters on the emulsification performances: Water/Tween80/Cyclohexane, Water/Tween80/Toluene, Water/PVA/Toluene and Water-Glycerol (25% weight)/PVA/Toluene. Cyclohexane was purchased from Acros

Table 1
Comparison between different on-line droplets size measurement techniques.

On-line Analysis technique	Experimental apparatus	Advantages	Drawbacks
Laser-induced fluorescence (Lan et al., 2006)	– Laser and optical system – Digital imaging system – Liquid–liquid flow system	– Measurement of in situ phase volume fraction, drop size, drop size distribution – Non intrusive – High dispersed phase ratio (up to 77% vol.)	– Fluorescent dye in the aqueous phase – Lab scale technique – Refractive index between the two phases
PVM (particle vision and measurement) Lasentec In situ video microscopy (O'Rourke and MacLoughlin, 2005)	– 10 images per second – Probe, light from 6 independent laser sources, region of illumination 2 mm², lensing system, CCD array	– In situ measurement	– 3 min to acquire the large number of images necessary for representative measurements : unsuitable for monitoring very rapid changes in size distribution
Optical methods	– Endoscope: short focal distance, covering tube to guarantee the optical transparency between the lens and the focus, fiber optic light guide, CCD camera and software for visualisation (Ritter and Kraume, 2000)	– Local measurement	– Transparent system, difference between the refractive index of the two phases – Large number of images must be acquired to construct the resulting size distribution – Time consuming
Phase Doppler interferometry	– Laser light wavelength	– Drop size and one component of drop velocity	– Unsuitable to applications involving high volume fractions of the dispersed phase
Laser backscattering technique-focus beam reflectance measurement FBRM Lasentec	– Backscattered light	– In situ and on line measurement	– Chord length of detected particles
Optical reflectance measurement (ORM) (Cull et al., 2002)	– Laser beam through a lens, rotating beam intercept a drop, the light is scattered back	– In situ and on line – Not limited by the dispersed phase because laser beam focused only at a short distance away from the instrument	– Chord length – Calibration
Light backscattering Turbiscan on-Line (Buron et al., 2004; Pizzino et al., 2009)	– Measurement of the backscattered intensity percentage	– No dilution – High dispersed phase ratio – Non intrusive	– Only the d_{32} – Knowing the dispersed phase volume fraction to obtain the d_{32} (and inversely)
Acoustic attenuation spectroscopy (Boscher et al., 2009)	– Based on frequency –dependent extinction of ultrasonic waves arising from particles – Droplet from 1 μm to 3mm	– Concentrated systems – On-line information: droplet characteristics and volume fraction of dispersed phase	– Difficulty to calibrate the system

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