Chemical Engineering Journal 191 (2012) 463–474

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Dispersed two-phase flow analysis by pulsed ultrasonic velocimetry in SMX static mixer

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ARTICLE INFO

Article history:
Received 3 August 2011
Received in revised form 22 February 2012
Accepted 29 February 2012

Keywords:
SMX
PUV
Two-phase flow
Dissipated energy
Macromixing
Mesomixing
Micromixing

ABSTRACT

Dispersed two-phase flow was experimentally investigated, by pulsed ultrasonic velocimetry (PUV) technique, in Sulzer SMX static mixers for turbulent flow regimes ($2280 < Re_P < 7980$). Data are reported for oil/water ratio of $\phi = 1\%$, 5% and 30% upstream, downstream and within the static mixer. Turbulence intensity as well as rate of mixing were tracked as function of Reynolds number. Most related studies considered the aspect of macromixing, by extracting the residence time distribution (RTD) of mixers which cannot properly reveal the complicated flow characteristics. Furthermore the information regarding micromixing efficiency in a static mixer is still lacking in the literature. In this work a global approach, based on the average and maximum velocity values and turbulence intensity, to estimate the time scale and process governing the mixing in the Sulzer SMX static mixer is discussed.

1. Introduction

Static mixers are widely used in the chemical process industry. Besides easy installation, enhancement of heat and mass transfer, generation of very high interfacial surface area, they have no moving parts, small space requirements, low or no maintenance cost and a short residence time. A good review of flow through static mixer was done by Thakur et al. [1]. Static mixers are available for different working conditions, i.e. laminar, transitional and turbulent flow regimes (Godfrey [2] and Myers et al. [3]). The mixer elements are designed to split the flow into two or more streams, rotate them and then recombine them for a better mixing and blending the most physical properties of fluid. Despite several decades of static mixers utilisation their characterisation has not been well understood due to the complexity of the flow structure within the SMX. Up to now, the comprehension of fundamental process remains insufficiently described [2]. However investigations on pressure drop, residence time distributions, experimental velocity profile from laser Doppler anemometry (LDA), friction factor by polarographic techniques, and the impact of the SMX on phase distribution are reported in the literature [4–11]. Furthermore, computational simulations with various CFD codes, supplemented experimental approaches [12–17]. However the lack of experimental data does not help in the validation of those numerical studies. Recently Legrand et al. [18] analysed the effect of a liquid dispersed phase on the wall flow structure in SMX by electrochemical method.

Knowledge of the velocity field and turbulence intensity is of interest for the inter-dependence with induced convective phenomena and mixing process [19–21]. In order to capture the main parameters intervening in such process fine investigation and measurements are required. Note that the scarcity of information about flow inside SMX static mixer is due to its complex structure, which makes non-intrusive investigation difficult. Hammoudi et al., [22] reported an investigation on the flow structure within the SMX by the pulsed ultrasonic velocimetry (PUV) method. The choice of pulsed ultrasonic velocimetry technique was based on its ability of measuring instantaneous velocity profile over the measuring line, its applicability to opaque pipes as well as emulsions with large concentration, mud, liquid metals [23–26].

The flows of reacting fluids through static mixers or agitated vessels can be very complex. For practical purposes, idealised models are necessary in order to describe the interaction of the resulting

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doi:10.1016/j.cej.2012.02.090

Nomenclature

C_{eff}	speed of sound in the medium (m/s)
C_C	speed of sound in continuous phase (m/s)
C_D	speed of sound dispersed phase (m/s)
D	diameter of control (m)
d_p	estimated pore diameter(m)
e	the size of blade (m)
f	frequency of emission (Hz)
f_D	Doppler frequency (Hz)
k	turbulent kinetic energy ($m^2 s^{-2}$)
l	represent the wall thickness (mm)
P_i	circumferential probe position (–)
Q	flow rate (m^3/s)
$Re = \frac{U_b D \rho}{\mu}$	Reynolds number (–)
$Re_p = \frac{U_p dp \rho}{\mu}$	pore Reynolds number (–)
$U_b = \frac{4Q}{\pi D^2}$	bulk velocity (m/s)
$U_P = \tau \frac{U_b}{\varepsilon}$	pore velocity (m/s)
V	axial component of velocity (mm/s)
x	x coordinate (m)
y	y coordinate (m)
z	z coordinate (m)
ε	turbulence dissipation rate ($m^2 s^{-3}$)
η	average porosity of the SMX: 0.9; average porosity of the SMX: 0.9
μ	dynamic viscosity (=0.779×10^{-3} Pa s)
ρ	density (=992) (kg/m^3)
$L_\tau = \frac{L}{H}$	tortuosity of the SMX = 1.48.
τ_C	macromixing circulating time (s)
τ_D	turbulent diffusion mesomixing time (s)
τ_E	engulfment micromixing time (s)
τ_S	inertial convective mesomixing time (s).

flow pattern with a chemical reaction or precipitation process. The mixing can quantitatively or even qualitatively alter the complex system dynamics when the mixing time is comparable to the reaction characteristic time [27].

These interactions take place on different scales, ranging from the macroscopic scale (macromixing) to the microscopic scale (micromixing). The concept of time mixing in different scale developed by Baldyga and Bourne [28] is based on diffusion and convection principles. According to the flow pattern, the reactor (static mixers) is divided into different zones with different flow characteristics velocity and turbulence intensity. Comprehensive models based on the engulfment–deformation–diffusion (EDD) theory incorporating the effects of vorticity were developed [28].

Most related studies considered the aspect of macromixing, by extracting the residence time distribution (RTD) of mixers [29–33]. However, it was pointed out that RTD cannot properly reveal the complicated flow characteristics in the static mixers [34].

In the present work the flow of dispersed oil in water in a vertical duct including a Sulzer static mixer was experimentally investigated. This was achieved for oil/water ratio of $\phi = 1\%$; 5% and 30% through measurements of velocity profiles as well as turbulent intensity upstream, downstream and within the static mixer. The experiments, based on pulsed ultrasonic velocimetry method, were conducted for three pore Reynolds number ($Re_p = (\rho_c d_p/\mu_c)(L_\tau U_b/\eta)$ of 2280, 4540 and 7980. The Re_p number is based on equivalent pore diameter, d_p, and pore velocity U_p, in order to take into account the porous structure of SMX static mixer [10–12,22]. The turbulence intensity as well as the mixing time scale, obtained from experimental data, gives appreciations on the rate of mixing with respect to the dispersed phase concentration and Reynolds number.

2. Experiments

The experimental set up as shown in Fig. 1 is a two-phase oil–water loop with a measuring section made of two identical parts, of 50 mm inside diameter and an overall length of 14 D, interconnected by a static mixer SMX containing 4 elements. The SMX-type is made of identical elements inserted in a housing tube of diameter D. The unit elements, constituting the SMX, are positioned one after the other with a circumferential shift of $\pi/2$, ensuring homogenisation of material properties [22]. It is advisable to recall that the number of blades of width equal to $e = 0.125$ D (Fig. 1c) contained in the duct are eight, two consecutive blades form an angle of 90° at the centre of the tube. The geometrical characteristics of the SMX static mixer are summarized in Table 1.

The ultrasonic probe can be displaced along the pipe and was localized as $Z_1 = -D$ upstream the SMX, $Z_2 = 4.7$ D downstream the latter and by $Z_0 = 3.5$ D within the fourth element of the mixer. It should be noted that the value used for the angle between the PUV probe and the tube axis Θ is 81° within the SMX, whereas on both sides mixer the value used is of 65° [22]. The first choice is governed by the skeleton of the matrix constituting the SMX while the second choice, corresponds to the commonly value adopted in the literature. The fluid properties are given in Table 2.

2.1. On the pulsed ultrasonic velocimetry technique (PUV)

The pulsed ultrasonic velocimetry is based on the use of echo sound of an ultrasound impulse emitted along a transducer measurement line. The latter records the signal reflected by surfaces of particles carried along by the fluid. The dispersed phase plays a role of a solid, liquid or gas tracer within a continuous phase which, in this case, is liquid.

The velocity information is extracted by measuring these frequency shifts. The measurement of the delay between the burst emission and its reception gives the position of the scattering volume. In this case the apparatus (DOP 1000, Signal Processing S.A.) gave the mean velocity, standard deviation, minimum and maximum velocities for each position using generally between 512 and 1024 emissions/profile. The recorded data generate the velocity profile and turbulence intensity [35].

In order to get a velocity profile the knowledge of the effective sound celerity C_{eff} in the medium, the attack angle θ of the ultrasound beam are of importance. The work of Mujica and Fauve [36,37] showed that C_{eff}, for a two-phase flow, is mainly dependant on temperature, pressure, salt concentration and void fraction. In the present case $C_C = 1509$ m/s for water at $T = 30$ °C. On the other hand Brito et al. [38] and Wang et al. [26] exhibit the importance of θ. In fact a slight deviation of one degree on θ value can induce a 30% error on the flow rate evaluation [35]. Therefore, a new approach of experimental determination of θ (attack angle) was conceived Hammoudi et al. [22].

The velocity is calculated from the following expression:

$$V = \frac{C_{eff} f_D}{2f \cos(\theta)} \tag{1}$$

where C_{eff} represents the sound effective celerity in the effective media formed by dispersed phase (oil) in proportion φ in a continuous phase (water) and is expressed such as:

$$C_{eff}^2 = \frac{1}{\langle\rho\rangle\langle\chi\rangle} = \frac{\rho_C \rho_D C_C^2 C_D^2}{(\rho_C(1-\varphi) + \rho_D\varphi)(\rho_D C_D^2(1-\varphi) + \rho_C C_C^2 \varphi)} \tag{2}$$

The determination of the sound celerity of the effective media depends strongly in one hand on the sound celerity in water, C_C,