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Hydrodynamics and residence time distribution of liquid flow in tubular reactors equipped with screen-type static mixers

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HIGHLIGHTS

- Pressure drop and RTD were investigated in reactors equipped with screen mixers.
- Effect of number and geometry of mixers, and operating conditions were studied.
- Less energy is required to drive the flow when compared to other motionless mixers.
- Axial dispersion was always minimized by the presence of screen mixers.
- Choosing the proper characteristic length to calculate Re is very important.

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ABSTRACT

This paper discusses the characteristics of liquid flow through tubular reactors/contactors equipped with woven mesh, screen-type static mixers from hydrodynamic and macromixing perspectives. The effect of changing the screen geometry, number of mixing elements, reactor configuration, and the operating conditions, were investigated by using four different screen types of varying mesh numbers. Pressure drop was measured over a wide range of flow rates ($2300 \leqslant \mathrm{Re} \leqslant 21{,}500$) and was found to increase with a decreasing mesh opening. Friction factor values are also reported in the work, when compared to other types of motionless mixers, screen-type mixers were found to require much lower energy requirements with very low recorded Z values ($1.15 \leqslant Z \leqslant 5$) that are two to three orders of magnitude lower than those reported for other motionless mixers.

Furthermore, residence time distribution experiments were conducted in the transitional and turbulent regimes ($2300 \leqslant \mathrm{Re} \leqslant 11{,}500$). Using a deconvolution technique the RTD function was extracted in order to quantify the axial/longitudinal dispersion. The findings highlight that regardless of the number and geometry of the mixer, reactor configuration, and/or operating conditions, axial dispersion coefficients that are lower than those of an empty pipe were always recorded. The wire diameter and mesh opening were found to directly affect the axial dispersion in the reactor, while, the number of elements showed a minor effect. Furthermore, the choice of the characteristic parameter used to calculate the Reynolds number was found to be of paramount importance in analyzing the data.

1. Introduction

Multiphase flow phenomena play an important role in the chemical and process industries. Such processes include unit operations carried out in batch and continuous stirred tanks, bubble and liquid–liquid extraction columns, as well as airlift reactors, amongst others. Optimizing the performance, economy and safety of these multiphase reactors/contactors is therefore of paramount importance. A proper understanding of the mixing process, if attainable, combined with an ability to predict the dynamic properties of the dispersion, such as drop/bubble size distributions and mass transfer performance, would therefore allow the introduction and implementation of major enhancements. However, due to the complex hydrodynamic conditions prevalent in most commercially available contactors/reactors, such achievements remain unreachable. Consequently, designing these units remains heavily dependent on the employment of empirical knowledge, experience, and extensive pilot-scale testing. Following the recent advances in computational fluid dynamics (CFD), the use of CFD as a design

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Nomenclature

Symbol	Description (unit)
b	screen wire diameter (m)
$C(t)$	normalized concentration of tracer (–)
$C_{in}(t)$	concentration of tracer measured at the inlet (mol/L)
$C_{out}(t)$	concentration of tracer measured at the inlet (mol/L)
$\widetilde{C}(\omega)$	FFT of the sampled inlet concentration (–)
COV	coefficient of variation (–)
D	empty pipe diameter (m)
D_{ax}	axial dispersion coefficient (cm^2/s)
$E(t)$	residence time distribution function (–)
f	fanning friction factor (–)
f_i	fanning friction factor calculated based on the screen open area (–)
k	total number of sampled points (–)
L	length of the mixing zone (m)
M	screen mesh opening (m)
MSE	mean squared error (–)
N	number of screen elements in the system (–)
Ne	Newton number (–)
p	fitting exponent (–)
Pe	Péclet number (–)
Q	volumetric flow rate (L/min)
Re	empty pipe Reynolds number (–)
Re_b	wire Reynolds number (–)
Re_{jet}	macroscopic jet Reynolds number (–)
Re_M	mesh Reynolds number (–)
$\widetilde{S}(\omega)$	FFT of the smoothing formula (–)
t	time (s)
t_m	mean residence time calculated from RTD (s)
U	superficial flow velocity (m/s)
V	volume of the mixing zone (L)
z	axial position in the pipe (m)

Greek symbols

α	fraction open area of the screen (–)
γ	fitting parameter (–)
ΔP	pressure drop in the mixing zone (kPa)
Θ	dimensionless time (–)
μ	viscosity (kg/m s)
ρ	density (kg/m^3)
σ^2	variance (s^2)
τ	theoretical residence time in the mixing zone (s)

tool to predict the performance and/or suggest alternative designs for multiphase reactor/contactor has been gaining strong momentum. The validity of this approach and its accuracy remains however the subject of a plethora of investigations in the open literature.

Nonetheless, plug flow reactors/contactors serve as a better choice when compared to other multiphase contactors/reactors in order to understand the complex phenomena taking place as well as providing better performance and control over mixing, breaking of drops and bubbles, as well as temperature [1–4]. The advantages of these conventional reactors lies however in their longer and controllable residence times as well as larger versatility for accommodating a variety of processing fluids. However, the growing interest in the use of tubular reactors equipped with static mixers, over conventional mixers, emanates from their inherent advantages whereby better performance can be achieved at lower capital and operating costs. Findings in the literature highlight the higher multiphase mass transfer and reaction rates that could be achieved in energy efficient manners while simultaneously handling large flow rates and achieving high heat removal or addition rates [1,3,5,6]. Furthermore, the insertion of properly-selected static mixing elements into tubular reactors allows for the introduction of the various reactants at different points along the reactor length, thereby facilitating the achievement of optimal temperature and reactant concentration profiles that are required to achieve optimal selectivity and conversion.

Woven mesh screen-type static mixers have been used to repetitively superimpose an adjustable, radially-uniform, highly-turbulent field on the nearly plug flow conditions encountered in high velocity pipe flows [7]. The very high energy dissipation rates present in the thin region adjacent to the screen are particularly effective in processing multiphase systems. This not only helps in the formation of fine dispersed phase entities (bubbles and/or drops) but also considerably enhances the value of the interphase mass transfer coefficient [6–9]. This is evidenced by their ability to promote contact between different phases, where interfacial areas as high as 2200 m^2/m^3 [10], and volumetric mass transfer coefficients, k_La, as high as 4.1 s^{-1} [11] could be achieved in the case of gas–liquid systems. In processing liquid–liquid systems, k_La values as high as 13 s^{-1} [8] were attained which enabled for 99% of equilibrium conditions be achieved in less than 1 s. Additionally, narrow and easy-to-separate drop size distributions with mean diameters in the order of 40 μm have also been reported [7,12]. This can be mainly attributed to the impact that high-intensity microscale turbulence, typically encountered in this mixer configuration, can have on the mass transfer coefficient [13]. In other terms, such good performance of screen-type static mixers, which is attributed to not only the formation of very fine dispersed phase entities but also enhanced mass transfer coefficients, is credited to the very high grid-generated turbulence and the consequent elevated micro-mixing intensities generated in the regions adjacent to the screens [14].

Similarly to other static mixers, screen-type mixers also offer the flexibility of designing the reactor to meet various mixing and/or energy requirements. For example, whereas a short inter-screen spacing favors the production of fine dispersions that are typical of high mass transfer rates and fast reactions, a longer spacing would be favorable for conditions of slow reactions and/or low energy requirements [6]. However, changing the reactor configuration and/or the operating conditions will impact the performance of the reactor by affecting its mixing efficiency and consequently the characteristics of the flowing dispersed phase along its length.

A frequently used technique to understand and quantify the actual flow phenomena in reactors/contactors is the residence time theory. This concept has been in place for over a hundred years [15] and became widely used after the work of Danckwerts in the early 1950's [15,16]. Residence time distribution (RTD) is an indicator of the macro-mixing in the reactor as it measures features of ideal or non-ideal flows associated with bulk flow patterns, and knowledge concerning its characteristics would therefore offer the ability to adapt the reactor/contactor design to meet specific process requirements.

RTD in static mixers, e.g. SMX, Kenics, etc..., was studied experimentally by several investigators for both Newtonian and non-Newtonian fluids [4,17–24]. The majority of these studies focused on measurements in the laminar flow regime and reported the data in the form of the RTD function or one of its moments. Keshav et al. [17] studied the RTD of the liquid phase in gas–liquid flow in Kenics mixer for air/Newtonian and air/non-Newtonian