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Pressure drop and axial dispersion in industrial millistructured heat exchange reactors

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ABSTRACT

Hydrodynamic characterization by means of pressure drop and residence time distribution (RTD) experiments is performed in three millistructured heat exchange reactors: two Corning reactors (further referred to as Corning HP and Corning RT) and a Chart reactor. Pressure drop is measured for different flow rates and fluids. Fanning friction factor is then calculated and its evolution versus Reynolds number is plotted for each reactor, showing the influence of the geometrical characteristics of the reactors on this parameter. From RTD experiments, axial dispersion coefficients that allow calculating Péclet numbers are identified by solving the convection-dispersion equation. The results highlight plug flow behavior of these reactors for the range of flow rates studied. Péclet number in Corning HP remains constant in the range of Reynolds number studied. Its specific pattern is designed to generate mixing structures that allow homogenization of the tracer over the cross-section. It explains the plug flow behavior of this reactor even at low Reynolds number but generates high pressure drop. Péclet number in Corning RT and Chart ShimTec® increases with Reynolds number. This evolution is encountered for straight circular pipes in turbulent regime and confirms the pressure drop analysis.

1. Introduction

The need to develop safer, more effective and less energy consuming processes while respecting environmental requirements caused since a few years the interest of the industry for the intensified technologies. In this context, heat exchange reactors are promising technologies [1]. Indeed it is difficult to control temperature in batch or semi-batch reactors when reactions are highly exothermic. Heat exchange reactors may offer a better thermal control of the reactions increasing safety and selectivity while reducing by-products generation. Continuous millistructured heat exchange reactors provide heat transfer at the closest of the reaction. They combine the advantages of millireactors (fast mixing, reactive volume confinement) and compact heat exchangers (high transfer area and large material mass per unit of reactive volume).

However, the miniaturization of the devices leads to low Reynolds number for the process fluid. To avoid pure laminar flow, instabilities have to be generated for mixing and transfer issues. Therefore millistructured devices are generally characterized by a complex geometry of the process channels to promote mixing, providing specific hydrodynamic behaviors notably in terms of pressure drop and Residence Time Distribution (RTD). Pressure drop is a key parameter to design a process since the cost of the pumps driving the fluid through the installation is generally a great part of the whole capital cost. RTD gives precious information on the hydrodynamics of the reactor and particularly on the axial dispersion generated. Axial dispersion is responsible of the spreading of the reactants and the products along the device which can lead to selectivity and conversion issues. This hydrodynamic parameter must thus be determined to correctly model the reaction [2].

The aim of this study is to provide and analyze the hydrodynamic behavior of three industrial millistructured reactors: two Corning fluidic modules and a Chart reactor. Elgue et al. [3] demonstrated the performances of these devices for the implementation of a chemical reaction. The authors carried out a two-phase esterification and observed higher conversion with the intensified millireactors than in batch conditions. Braune et al. [4]

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Nomenclature

c	Concentration of tracer ($\mathrm{mol\,m^{-3}}$)
D_{ax}	Axial dispersion coefficient ($\mathrm{m^2\,s^{-1}}$)
D_h	Hydraulic diameter of the tube (m)
D_m	Molecular diffusion coefficient of tracer in solvent ($\mathrm{m^2\,s^{-1}}$)
E	Distribution function ($\mathrm{s^{-1}}$)
f	Fanning friction factor (–)
J	Number of stirred tanks (–)
L	Length of the reactor (m)
P	Perimeter of the cross section (m)
Pe	Péclet number (–)
Q	Flow rate ($\mathrm{m^3\,s^{-1}}$)
Re_h	Hydraulic Reynolds number (–)
$Re_{\sqrt{S}}$	Square section Reynolds number (–)
S	Cross section of the channel ($\mathrm{m^2}$)
s	Minimization function ($\mathrm{mol^2\,s\,m^{-6}}$)
t	Time (s)
$t_{r,exp}$	Experimental residence time (s)
u_0	Average velocity ($\mathrm{m\,s^{-1}}$)
V	Volume ($\mathrm{m^3}$)
x	Longitudinal coordinate (m)

Greek letters

μ	Dynamic viscosity (Pa.s)
ρ	Density ($\mathrm{kg\,m^{-3}}$)
ΔP	Pressure drop (Pa)

Subscripts

calc	Calculated
exp	Experimental
in	Inlet of the reactor
out	Outlet of the reactor
square	Square section

then Buisson et al. [5] also demonstrated the efficiency of mass transfer in Corning mixing module by performing selective reactions. Pressure drop and residence time distribution in Corning reactors have already been investigated [6,7] and residence time distribution have also been studied in Chart ShimTec® based technology by Cantu-Perez et al. [8]. However, the experiments were carried out with water for pressure drop measurements and generic correlations are missing to estimate the hydrodynamic behavior using quantitative parameters.

In the present work, pressure drop and RTD experiments are carried out. They are analyzed in order to suggest correlations for the estimation of dimensionless numbers characteristic of the hydrodynamics of reactors such as Fanning friction factor and Péclet number. The impact of the geometry of the three devices on the pressure drop and the RTD results is also discussed. The first part of this paper presents the reactors design and the experimental setup. The pressure drop results are presented in a second part. Then, the RTD experiments and the methodology to identify the Péclet number are described. The results are compared to models available in literature.

2. Experimental method

2.1. Description of the reactors

The devices tested are two Corning fluidic modules G1 based on the Corning Advanced-Flow™ technology [9] and a Chart reactor based on the ShimTec® technology [10] (Fig. 1).

Corning modules are made of three glass parts. The first Corning module (hereinafter called Corning RT for Residence Time) is composed of one plate carved by a single rectangular channel with 180° bends. The second module (hereinafter called Corning HP for Heart Pattern) is based on a Heart Pattern designed to generate mixing structures (51 hearts by plate). Each process plate is combined with two utility plates that allow to control the temperature of the reaction. These modules can be used in series to form a complete reactor. The Chart ShimTec® reactor is composed of thin plates (also called shims) that include the channels of the reactor. They are bonded together to create the whole structure. It is composed of three parallel process channels. The reactor can be fed by a utility fluid for heat exchange purpose. These three reactors are designed for specific applications. Corning RT is made to pre-heat reactants before a reaction plate or to add residence time at the end of the setup. Corning HP is likely used for two-phase reactions that need intensified mass transfer. Chart ShimTec® reactor is designed to produce low pressure drop to perform reactions with viscous fluids. Their characteristic dimensions are given in Table 1. It is difficult to estimate the length of Corning HP reactor since its section is not constant. However, the RTD results are used to identify the equivalent cross section and length of the reactor. Indeed, these parameters are fitted by comparing the shapes of the experimental and calculated outlet RTD curves and the experimental and theoretical residence times (see Appendix A). Nevertheless, even if these equivalent characteristics are not perfectly reliable, they do not affect the identification of hydrodynamic behaviors as function of the reactor geometry. For the Chart ShimTec® reactor, the equivalent length is the average length of the 3 channels. For the RTD experiments, it is considered that the output RTD curves can be decomposed into three distinct curves representing the path of the tracer in the three channels of

Table 1
Reactors dimensions.

	Corning RT	Corning HP	Chart ShimTec®
Equivalent cross section S ($10^{-6}\,\mathrm{m^2}$)	3.8	4.6	4.0 × 3 channels
Equivalent length L (m)	2.0	2.5	1.5

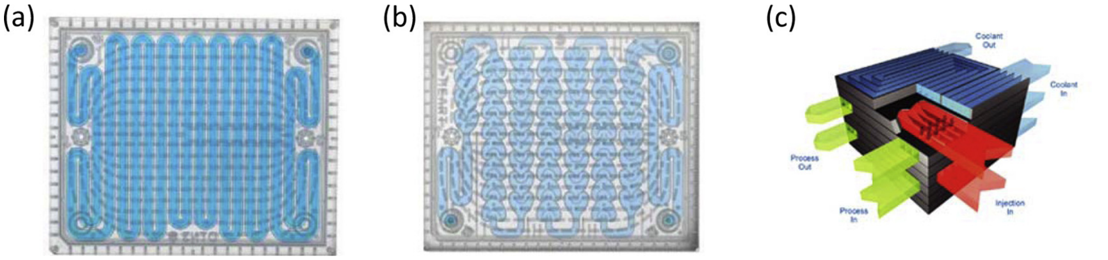

Fig. 1. Millistructured reactors: (a) Corning RT, (b) Corning HP and (c) Chart ShimTec® [9,10].