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Influence of the meandering channel geometry on the thermo-hydraulic performances of an intensified heat exchanger/reactor

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ABSTRACT

In the global context of process intensification, heat exchanger/reactors are promising apparatuses to implement exothermic chemical syntheses. However, unlike heat exchange processes, the implementation of chemical syntheses requires to control the residence time to complete the chemistry. A way to combine the laminar regime (i.e. enough residence time) with a plug flow and the intensification of both heat and mass transfers is the corrugation of the reaction path.

In this work, the experimental set-up is based on plate heat exchanger/reactor technology. 7 milli-channel corrugated geometries varying the corrugation angle, the curvature radius, the developed length, the hydraulic diameter and the aspect ratio have been designed and experimentally characterized (heat transfer, mixing times, pressure drops, RTD). The objectives were to assess their respective performances to derive some correlations depending on the channel design.

The results confirmed the benefits of the reaction channel corrugation. Heat and mass transfers have been intensified while maintaining a plug flow behaviour in the usually laminar flow regime. Moreover, whatever the meandering channel's curvature radius, the results highlighted the relevance of considering the Dean number as the scale-up parameter. This dimensionless number, more than the Reynolds number, seems to govern the flow in the wavy channels.

1. Introduction

In the global context of process intensification, defined by Stankiewicz and Moulijn [1] as "any chemical engineering development that leads to a substantially smaller, safer, cleaner and more energy-efficient technology", heat exchanger/reactors are promising apparatuses [2,3]. Indeed, by combining a reactor and a heat exchanger in only one unit the heat generated (or absorbed) by the reaction is removed (or supplied) much more rapidly than in a classical batch reactor. As a consequence, heat exchanger/reactors may offer better safety (by a better thermal control of the reaction), better selectivity (by a more controlled operating temperature) and by-products reduction (in case of temperature-dependent secondary reaction for instance).

The main interesting ways to intensify heat and mass transfers in heat exchanger/reactors are to insert 3D elements like metallic foams or fins [4–6] or to structure the flow path (2D or 3D) [7–13]. Such apparatuses have to address many points in terms of performances, but also in terms of polyvalence (the technology should not be dedicated to only one application), flexibility (to easily switch from one flow regime to another), competitiveness (too complex geometries lead to too high manufacturing and operating costs) and scale-up (performances have to be maintained during the scale-up procedure).

To optimize the heat exchanger/reactor performances vs. the investment capacity, the first step is to characterize the flow behaviour and the transfer mechanisms [8,14]. This is one of the objectives of this work. A 2D-structured millimetric and meandering process channel is considered. Contrary to the flow in a straight channel, the streamlines in a corrugated flow are not parallel to the flow axis. The centrifugal force encountered in each bend and the imbalance between this force and the pressure gradient generate counter-rotating vortices in the channel cross section. W.R. Dean [15] was the first to solve the flow solution in a curved duct. He defined the Dean number, De, which takes into account the secondary loops generated in a corrugated channel:

$$\mathrm{De} = Re \times \sqrt{\frac{d_h}{R_c}} \quad (1)$$

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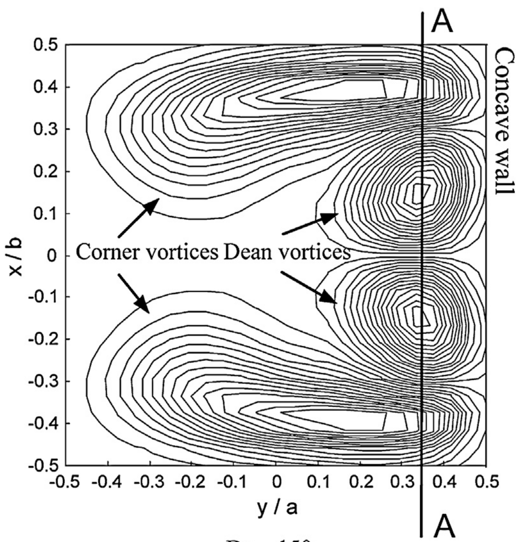

Fig. 1. Visualization of the secondary loops in a square duct cross section [16].

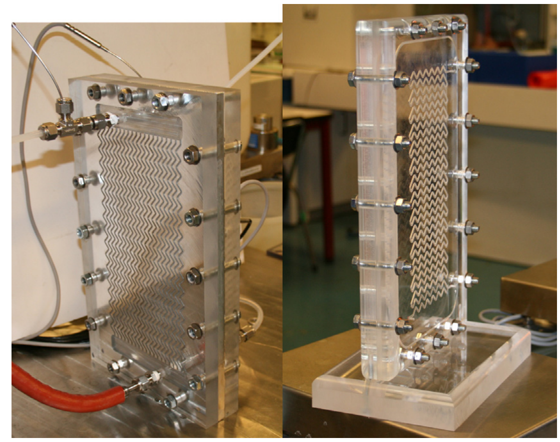

Fig. 2. View of the process channels without the utility plate (right side) and view of the utility channels ((left side).

Re is the Reynolds number,

$$Re = \frac{\rho \times u \times d_h}{\mu} \tag{2}$$

ρ, μ and u are respectively the flow density (kg m^{-3}), viscosity (Pa s) and velocity (m s^{-1}).d_h is the channel hydraulic diameter (m) and R_c is the curvature radius (m).

An increase of the Dean number tends to move the axial velocity peak from the centre to the outward duct wall. Above a critical value of the Dean number, because of the flow instability, two additional vortices appear. They are called the Dean vortices. Fig. 1 illustrates this flow phenomenon.

The critical Dean number ranges between 100 and 250 according to the employed Dean vortices detection method [16–18]. Downstream each bend, the flow tends to a laminar flow in the straight length. By alternating the corrugations, the flow instabilities are reactivated in each bend which promotes the radial homogenization of the velocity, temperature and momentum fields [19].

On the other hand, this expected gradients homogenization has to be balanced with a pressure drop increase. The goal of this work is thus to optimize the corrugated channel geometry in order to intensify the heat and mass transfers while getting a low Reynolds number flow. This last point is required to have reasonable residence time (to complete the chemistry) and low pressure drop.

Moreover to expect a future industrialization of heat exchanger/reactor technologies, the scalability is another major step to study. Indeed, during the scale-up procedure, each similitude law (hydrodynamics, chemistry, geometry,...) should be verified in order to maintain the performances. However each law is characterized by its own invariant parameter (time, length,...) and it is often impossible to verify the principle of similitude:

$$G_{mock-up} = \mathrm{k} \times G_{pilot}, \text{ with k a constant parameter} \tag{3}$$

It is thus required to characterize the effect of the scale-up on the performances of our system. The 2nd objective of this work is then to deduce rules and correlations which will be used to predict the performances of the meandering channel at a pilot scale.

In the present work, a plate-type heat exchanger/reactor, including one process plate and one cooling plate, has been studied. On each plate, a wavy milli-channel has been mechanically etched. This work aims at characterizing the flow performances in several geometries in terms of residence time distribution, mixing times, heat transfer and pressure drops. Both the influence of the channel geometry and the influence of the channel characteristic sizes (hydraulic diameter and aspect ratio) have been studied. Seven geometries have been considered and a mock-up has been built for each one.

2. Materials and methods

2.1. Experimental mock-ups

The mock-ups are made of three plates: a cooling plate sandwiched between a closing plate and a 'process plate' in which the reactants are flowing co-currently. The cooling plate is a 7 mm thickness aluminium plate with a high thermal conductivity ($\lambda = 247$ W m^{-1} K^{-1}). It is used during thermal experiments and is removed for the hydrodynamic characterizations. Both the closing and 'process' plates are made of PolyMethylMethAcrylate (PMMA), whose thermal conductivity, coupled to a thickness of 20 mm, is low enough to avoid thermal losses ($\lambda = 0.19$ W m^{-1} K^{-1} and $\lambda/e = 8.5$ W m^{-2} K^{-1}; negligible in comparison with the local heat transfer coefficients). The transparency of these plates is necessary in order to visualize the flow in the channel during mixing experiments. To test various channel designs, the mock-ups have to be easily and quickly implemented. As a consequence, each plate is etched in the laboratory with a numerically controlled milling machine. Then, the plates are assembled with 16 clamping screws for the thermal experiments (see Fig. 2), or chemically bonded for the hydrodynamic tests.

Each mock-up is connected to a test bench equipped with 2 magnetic drive pumps (Verder, 0–5 and 0–10 L h^{-1}), three mass flow metres (Micromotion), a differential pressure measuring transducer (Rosemount, 0–5 bars), 12 temperature probes (Pt100 and thermocouples), two spectrophotometers (AvaSpec 2048, AvaLight DHc and In-line flow cells Avantes) and a syringe pump. Experimental data (temperature, flowrate, pressure and absorbance) are recorded by an on-line data storage system.

2.2. Geometrical parameters of the wavy channels

Two main challenges have to be addressed when structuring the wavy channels:

- How can *a plug flow* and *a sufficient residence time* for the chemistry be combined?