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HYDRODYNAMIC STUDY AND OPTIMIZATION OF THE GEOMETRY OF A WAVY CHANNEL IN AN INTENSIFIED HEAT EXCHANGER/REACTOR.

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Abstract. The implementation of chemical syntheses in batch or semi-batch reactor is generally limited by the removal or the supply of heat. A way to enhance thermal performances is to develop multifunctional devices like heat exchanger/reactors. Then, to improve yields, selectivity and safety in such apparatuses, mass transfer has to be enhanced. One of the interesting ways to intensify the mass transfer is to structure the wavy channel etched on each plate. A plate-type heat exchanger/reactor has been studied in this work. The influence of the geometrical parameters (corrugation angle, aspect ratio, curvature radius and straight length) of the etched wavy channel on residence time distribution (RTD), mixing performances and pressure drop has been experimentally investigated. Five geometries have been tested and a mock-up has been designed and built for each one. It was shown that reducing the curvature radius (from 4 to 1.5mm) is interesting to promote the mass transfer (development of Dean vortices) with a moderate increase of the pressure drop for low Reynolds numbers. The increase of the straight length (from 7 to 20mm) allows a decrease of the pressure drop without any significant effect on the mixing performance. Moreover, it was shown that increasing the aspect ratio from 0.5 (rectangular cross section) to 1 (square cross section) has a negative impact on the RTD but enhances the mass transfer. Finally, the corrugation angle seems not to have any effect on mass transfer, RTD and pressure drop.

Keywords. Heat exchanger/reactor, wavy channel, mass transfer, Dean instabilities, intensification.

INTRODUCTION

In the global context of process intensification; defined by Stankiewicz and Moulijn¹ as “any chemical engineering development that leads to a substantially smaller, safer, cleaner and more energy-efficient technology”; heat exchanger/reactors are promising apparatuses². 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 (through a better thermal control of the reaction), better selectivity (through more controlled operating temperature) and by-products reduction (in case of temperature-dependent secondary reaction for instance)³. Moreover, improving the mass transfer in such an apparatus could drastically enhance its performances in terms of yields, selectivity and safety (by avoiding the accumulation of reactants for instance). In the present work, a plate-type heat exchanger/reactor, including one process plate and one utility plate, has been studied. On each plate, a wavy channel has been mechanically etched. One of the interesting ways to intensify the heat and mass transfers is to structure the channel (2D or 3D). This work aims at studying the influence of the geometrical parameters of the wavy channel on residence time distribution, global mixing and pressure drops. Five geometries have been studied and a mock-up has been built for each one. Experimental results have been completed with numerical ones in order to visualize the flow structures. Finally, to complete this work, thermal characterizations have been performed in these mock-ups⁴.

EXPERIMENTAL SETUP

Before scaling-up the plate-type heat exchanger/reactor, the geometry has to be studied and optimized at lab-scale which involves experimental characterizations of the various channel geometries. That is the reason why the mock-ups have been designed and built.

Design and implementation of the mock-ups

The mock-ups are composed of three plates: a cooling (or heating) plate called ‘utility plate’ sandwiched between a closing plate and a ‘process plate’ in which flow the reactants. The ‘utility plate’, made of aluminium, is used during thermal experiments and is removed for the hydrodynamic characterizations. The ‘closing’ and ‘process’ plates are made of PolyMethylMethAcrylate (PMMA) which is transparent in order to visualize the flow in the channel during the mixing experiments. In order to test many channel designs, the mock-ups have to be easily and quickly implemented. As a consequence, each plate was etched within the laboratory with a numerically controlled milling machine. Then, the plates are assembled with 16 clamping screws (see figure 1).

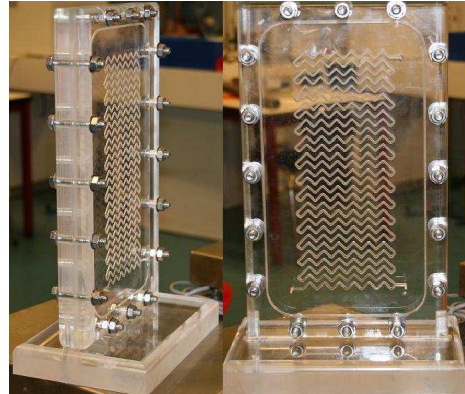


Figure 1. Views of the process channel of one of the mock-up.

Each mock-up is, then, connected to a test bench equipped with 2 magnetic drive pumps; three mass flowmeters; a differential pressure measuring transducer, 12 temperature probes (Pt100 and thermocouples), two spectrophotometers and a syringe pump. Experimental data (temperature, flowrate, pressure and absorbance) are recorded by an on-line data storage system.

Geometrical parameters of the wavy channel

Two main challenges have to be taken up when structuring wavy channels:

- How can we combine a *plug flow* and a *sufficient residence time* for the chemistry?
- How can we combine a *laminar flow* (in order to get a sufficient residence time and low pressure drop) and the *intensification* of mass and thermal transfers?

So as to determine the optimal geometry with respect to these criteria, the influence of the geometrical parameters on residence time distribution, mixing performances and pressure drops has to be studied. These parameters were chosen with regards to those commonly studied in literature (see table 1).

Table 1. Summary of literature data.

Authors	Studied geometrical parameter(s)	Adimensional number(s) on which the study is based
Cheng <i>et al.</i> ⁵	Aspect ratio, a/b	Critical Dean number
Fellouah <i>et al.</i> ⁶	Curvature radius, R_c	Critical Dean number
Chandratilleke <i>et al.</i> ⁷	Aspect ratio, a/b	Critical Dean number
Ligrani <i>et al.</i> ⁸	Aspect ratio, a/b	Nusselt number
Aubin <i>et al.</i> ⁹	Aspect ratio, a/b	Residence time distribution
Hwang <i>et al.</i> ¹⁰	Aspect ratio, a/b	
Rosaguti <i>et al.</i> ¹¹	Curvature radius, R_c	
Comini <i>et al.</i> ¹²	Corrugation pitch	
Lin <i>et al.</i> ¹³	Corrugation angle, θ	Nusselt number and friction factor
Pham <i>et al.</i> ¹⁴		
Stasiek ¹⁵	Corrugation angle, θ ; corrugation pitch and corrugation height	

From these data, four parameters seem to be important (see figure 2): the aspect ratio, a/b; the curvature radius, R_c ; the corrugation angle, θ and the straight length, L_d which corresponds to the length between two bends. The corrugation pitch and the corrugation height will vary with the straight length. In order to dissociate the influence of each parameter on hydrodynamic performances and pressure drop, only one parameter

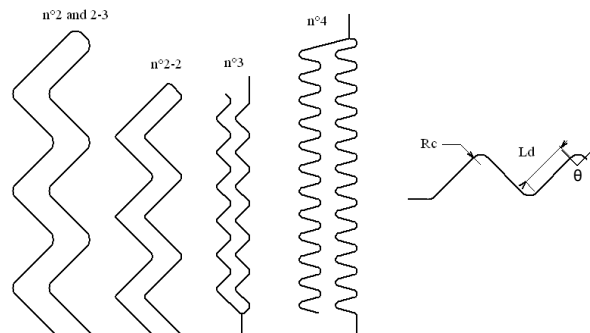


Figure 2. Schematic view of the corrugated channels and of the geometrical parameters.

varies from one mock-up to another. The geometrical data are given in table 2.

Table 2. Geometrical data of the corrugation parameters.

Mock-up n°	a/b	$d_{h,eq}$	θ	R_c (mm)	L_d (mm)	L_{tot} (m)	V_{tot} (cm ³)
2	0.5 (2/4mm)	2.67	90°	4	20.28	3.4	27.2
2-3	1 (2/2mm)	2	90°	4	20.28	3.4	13.6
2-2	1 (2/2mm)	2	90°	1.5	20.28	3.5	14.0
3	1 (2/2mm)	2	90°	1.5	6.94	3.5	14.0
4	1 (2/2mm)	2	30°	1.5	6.94	5.0	20.0

CHARACTERIZATIONS AND RESULTS

This paper focuses on pressure drop, residence time distribution and mixing performances. In order to study the influence of each parameter on the mock-up performances, these three experimental characterizations have been performed.

Pressure drops

The experimental determination of pressure drops aims at correlating the Darcy coefficient, Λ , with the Reynolds number. In literature, the general expression is written:

$$\Delta P = \Lambda \cdot \frac{L}{d_{h,eq}} \cdot \rho \cdot \frac{u^2}{2}$$

This correlation is characteristic of the size and the geometry of the channel as shown in figure 3. Experiments have been made with water (20°C) in a Reynolds number range from 150 to 2200.

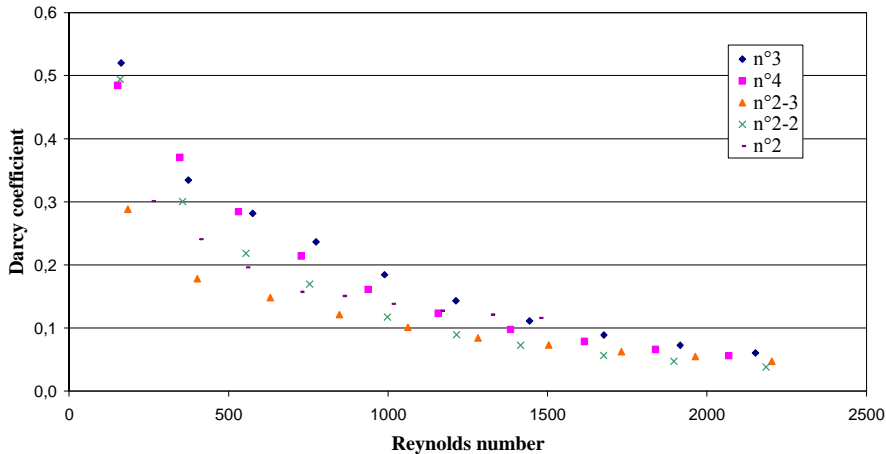


Figure 3. Experimental Darcy coefficient for each mock-up.

Results show that the angle of corrugation (90° or 30°) has no influence on pressure drop (mock-up n° 3 and 4). However, when the straight length increases from 6.94mm (mock-up n°3) to 20.28mm (mock-up n°2-2), the pressure drop decreases. This is the influence of the number of bends per unit of length which is less in the mock-up n°2-2 than in n°3. A decrease of the pressure drop is also observed when the curvature ratio increases from 1.5mm (mock-up n°2-2) to 4mm (mock-up n°2-3). This result is due to the development of Dean vortices in each bend¹⁶ that promote heat and mass transfers to the detriment of pressure drop. Dean number is written:

$$De = Re \cdot \sqrt{\frac{d_h}{R_c}}$$

So the smaller the curvature radius is, the higher the Dean number is. Above a critical Dean number⁶, the geometry has no more influence on the development of the vortices that is the reason why the pressure drop are quite the same at high Reynolds number (above 1500).

Residence Time Distribution (RTD)

RTD experiments have been carried out in order to characterize the hydrodynamic behaviour in each geometry. A spectro-photometric technique that entails a coloured tracer has been used. Two measuring probes

are set up at the inlet and at the outlet of the mock-up. The acquisition time is set to 0.12s. Each experiment has been performed at room temperature with a flow rate varying from 5 to 18 kg.h⁻¹ (Reynolds number range from 450 to 2500). Figure 4 shows the RTD obtained for the mock-up n°2 (a/b=0.5) and the mock-up n°2-2 (a/b=1).

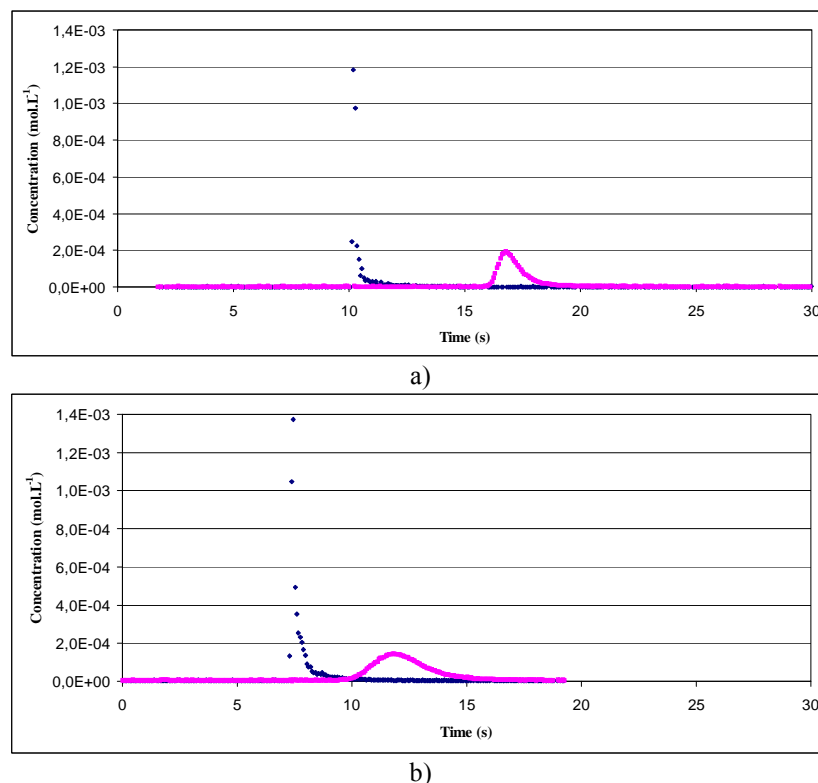
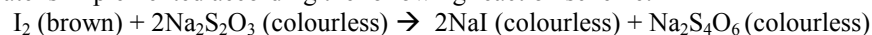


Figure 4. RTD function of the aspect ratio ($F=17 \text{ kg.h}^{-1}$). a) Mock-up n°2 ($a/b=0.5$); b) Mock-up n°2-3 ($a/b=1$).

As shown in figure 4, the aspect ratio has a significant influence on RTD. Indeed, when the aspect ratio increase from 0.5 (2/4mm; mock-up n°2) to 1 (2/2mm; mock-up n°2-3), the Peclet number decreases from 400 to 150 which means that the hydrodynamic behaviour of the mock-up n°2 is closer to the behaviour of a plug flow than in the mock-up n°2-3. However, in both cases, the Peclet number is high enough to consider that the flow behaviour is similar to the one of a plug flow. This result is true for each geometry whose graphs are not presented in this article. Finally, RTD experiments did not reveal any significant influence of the other geometrical parameters (θ , R_c and L_d) on the flow behaviour.

Mixing performances

To characterize the mixing level of each mock-up, the reaction of discolouration of an iodine solution with sodium thiosulfate is implemented according the following reaction scheme:



This homogeneous reaction is instantaneous and mixing limited. As a consequence, at steady state, by measuring the required length to complete the discolouring of iodine, the mixing time can be easily determined. Operating conditions are given in table 3 and figure 5 shows the mixing time versus the Reynolds number.

Table 3. Operating conditions for the characterization of mixing in each mock-up (the ratio between the flow rates is equal to 1).

$C_i \text{ (mol.L}^{-1}\text{)}$	$C_t \text{ (mol.L}^{-1}\text{)}$	$F_i+F_t \text{ (L.h}^{-1}\text{)}$
$5 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	1
		1.5
		2.25

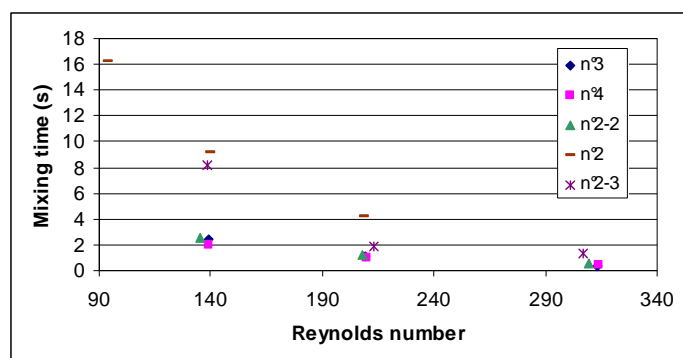


Figure 5. Mixing time versus Reynolds number for each mock-up.

Experimental results show that there is no influence of the corrugation angle, θ (mock-up $n^{\circ}3$ and 4) on mixing time. Moreover for low Reynolds number (between 140 and 220), when the curvature radius increases from 1.5mm (mock-up $n^{\circ}2-2$) to 4mm (mock-up $n^{\circ}2-3$) the mixing time increases. This is the consequence of the Dean vortices which promote mass transfer and the smaller the curvature radius, the higher the Dean number. However, these vortices tend to disappear along the straight length until the following bend. As a consequence, the shorter the straight length, the faster the vortices are developed again, thus promoting mass transfer. Mixing experiments shown no influence of the straight length (mock-ups $n^{\circ}3$ and $n^{\circ}2-2$). As a consequence, a straight length of 20.28mm seems enough to maintain the vortices between two bends, thus decreasing the pressure drop. Finally, when the aspect ratio increases from 0.5 (mock-up $n^{\circ}2$) to 1 (mock-up $n^{\circ}2-3$), the mixing time decreases. Actually, Dean vortices are formed close to the wall of the channel. In case of an aspect ratio of 1, Dean vortices fill the whole cross section whereas in case of an aspect ratio equal to 0.5, the central part of the cross section is not reached by the vortices. That is the reason why mixing is less efficient in the mock-up $n^{\circ}2$ than in the mock-up $n^{\circ}2-3$. This result has been confirmed by numerical simulations (CFD code) which are not presented in this article.

CONCLUSION

The influence of the geometrical parameters of a wavy channel on residence time distribution (RTD), mixing performances and pressure drop has been investigated in this work. The experimental results show that a compromise has to be found between the enhancement of mass transfer, the pressure drop and the RTD. It appears that the curvature radius, the aspect ratio and the straight length are important parameters. Indeed, the decrease of the former is linked to the development of Dean vortices, thus promoting mass transfer without any impact on the RTD whereas the straight length has to be chosen so as to maintain these vortices between two bends. These results are in agreement with the ones of the thermal characterization⁴ whereas, concerning the aspect ratio, two opposing effects are observed. Indeed, the increase of the aspect ratio promotes a plug flow behaviour⁹ whereas mass transfer is reduced. A compromise has to be found. Finally, the corrugation angle seems not to have any effect on mass transfer, residence time distribution or pressure drop.

According to the results of this study and the results of the thermal characterization⁴, a first geometry can be proposed: the corrugation angle will be set at 90° , the curvature radius at 1.5mm. The straight length could be increased until 15mm. Concerning, the aspect ratio, numerical investigations will be necessary in order to adjust this parameter. Then, since all the geometries have been technologically validated in parallel works¹⁷, a pilot mock-up would be built and characterized. This will be the first step of an extrapolation procedure¹⁸ before the industrial scale.

NOMENCLATURE

- a: Channel width (m)
- b: Channel height (m)
- C: Molar concentration (mol.L^{-1})
- $d_{h,eq}$: Equivalent hydraulic diameter (m)
- \mathcal{D}_A : Axial dispersion coefficient (m.s^{-2})
- De: Dean number
- F: Volume flow rate (L.h^{-1})
- L_d : Straight length between two bends (m)

L_{tot} : Total channel length (m)
 Pe : Peclet number; $Pe = \frac{u \cdot L_{tot}}{\mathcal{D}_A}$
 R_c : Curvature radius (m)
 u : Fluid velocity ($m \cdot s^{-1}$)
 V_{tot} : Total channel volume (m^3)
 θ : Corrugation angle
 Λ : Darcy coefficient
 ρ : Fluid density ($kg \cdot m^{-3}$)
Subscripts:
 i : Iodine solution
 t : Thiosulfate solution

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