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# Flow in a X junction: influence of the intersection angle and aspect ratio of the section on the flow redistribution

M. Cachile<sup>a</sup>, JP Hulin<sup>b</sup>, H. Auradou<sup>a,b</sup>, L. Talon<sup>b</sup>

- a. Grupo de Medios Porosos, Facultad de Ingeniería, Paseo Colon 850, 1063, Buenos Aires (Argentina)  
 b. Univ Pierre et Marie Curie-Paris 6, Univ Paris-Sud, CNRS, F-91405. Lab FAST, Bât 502, Campus Univ, Orsay, F-91405 (France).

## Résumé :

Expérimentalement, de l'eau et de l'eau colorée sont injectées dans une jonction en X formée de canaux de sections rectangulaire. La distribution des écoulements à la sortie est déterminée par fluorescence. L'étude considère l'effet de l'angle et du rapport d'aspect des sections sur la répartition des fluides. Les mesures montrent que la majeure partie d'un fluide injecté sort dans celui des canaux de sortie qui fait un angle aigu avec le canal d'injection (le contraire est attendu pour des écoulements inertiels). Dans l'autre canal, la proportion (minoritaire) décroît de 50 % pour un angle de  $90^\circ$  à 0 pour  $35^\circ$ . Des simulations numériques montrent qu'en dessous de  $33.8^\circ$ , apparaissent dans la partie centrale de la jonction des cellules de recirculation qui séparent les écoulements. On discutera l'évolution de ces résultats lorsqu'on change le rapport d'aspect des canaux en réduisant leur ouverture dans le plan de la jonction.

## Abstract :

Experimentally, water and dyed water are injected in a X-junction formed by channel of rectangular cross sections (width  $w$  and height  $h$ ). The distribution of the flow at the outlet is measured by laser induced fluorescence. The effect of the crossing angle ( $\alpha$ ) and of the aspect ratio of the section on the flow distribution are studied. The measurements show the most of the fluids are flowing through the channel making the (the opposite is expected at for higher Reynolds number). In the other canal, the proportion of fluids continuously decreases from 50 % for an angle of  $90^\circ$  to 0 for  $\alpha = 35^\circ$ . Numerical modelisations show that below  $33.8^\circ$  and for squared sections, recirculation cells in the central part of the junction appear. The influence of the aspect ratio of the channel section on the flow distribution will be discussed.

**Mots clefs : 3 maximum : mot-clef1 ; mot-clef2 ; mot-clef3**

## 1 Introduction

Flow control in crossing channels of sizes going from micro - milli to centimetric scales is an important area of research in engineering. The behavior of the fluids at junctions is critical for applications such as mixing [1], production of microbubbles [2], chemical reactions [3, 4] or heat exchange [5, 6]. Past studies mostly concerned Tees junctions [7, 4] or X-junctions intersecting at right angle (*i.e.* with  $\alpha = \leq 90^\circ$ ) [8], the present work analyzes the influence of the intersecting angle  $\alpha$  and of the aspect ratio  $AR$  ( $= h/w$ , where  $h$  is the height and  $w$  is the width of the channels). More precisely, the two fluids of same viscosity and density are injected in facing channels and we study the relative fraction in each of the outlet channels. The system is studied by combining experimental *PLIF* measurements on transparent models and 2D numerical simulations. Like for Fan and Hassan [9] or Tan et al [4], the channels have a millimetric scale in order to visualize conveniently the flow; however, the Reynolds number  $Re = \rho aU/\eta$  is low enough so that inertial effects are negligible and the Stokes equation is

satisfied ( $U$ ,  $\rho$  and  $\eta$  are respectively the mean velocity, density, and viscosity of the fluid and  $a$  is the width of the channels). The flow velocity field is therefore the same as in much smaller microchannels of same geometry.

## 2 Methods

### 2.1 Experimental procedure

The channels are carved into a transparent plexiglas plate by a computer controlled milling machine ; both their width  $w$  and depth  $h$  and the intersection angle  $\alpha$  are controlled. A second technic using Mylar sheets of  $500\mu\text{m}$  thickness on which the channels are cut was also developed. In this case, the sheets are placed between two clamped glass plates. Each outlet is connected to one of the inlets of a double syringe pump sucking the fluids at equal flow rates. The two facing inlet channels are connected to two flasks containing respectively pure water and a solution of water containing  $0.25\text{ mg.l}^{-1}$  of rhodamin 6G. The two fluids have the same viscosity and very close densities so that no buoyancy or viscosity driven instabilities are observed. For most of the experiments, each bottles are placed on computer controlled scales allowing for a measurement of the flow rates. In the present work, these flow rates are set to be equal within  $\pm 0.3\%$  by adjusting the relative levels of the fluid in the flasks. The distribution of the two fluids in the intersection is visualized by the Planar Laser Induced Fluorescence (PLIF) technique. A plane horizontal green laser sheet and thickness  $\simeq 1\text{ mm}$ , parallel to both channels, enters the model from the side. The parts of the channels containing the rhodamin dye solution are easily identified by the emission of a yellow fluorescence light. The distribution of this solution in the illuminated plane is then recorded by a digital camera equipped with a filter and placed above the model. With this procedure, regions in which only water is present appear as dark while those containing rhodamin are illuminated (Fig. 1). Finally, the distribution of each fluids in the outlets is characterized by measuring  $a_d$  the width of the fluorescent stream.

## 3 Results

A first key observation is that, for all angles  $\alpha$ , each injected fluid flows dominantly towards the outlet at the lowest angle with the injection channel (outlet 1 for the fluorescent solution in Fig.1) : this corresponds to flow paths with a higher curvature than those leading to the other outlet. The flow of each fluid is equally split between the outlets only for  $\alpha = 90^\circ$  [8]. At  $\alpha = 45^\circ$ , the fraction of light fluid moving towards outlet 2 is small and is exactly zero for  $\alpha = 30^\circ$ . In this latter case, all incoming fluorescent streamlines are blocked on the junction towards outlet 1 (See 1). The main flows of the two fluids are then completely separated.

As show in Fig.1c, the blockage of the flow is due the occurrence of a recirculation cell developing between two corners of the junction. In a previous study, we have demonstrate that for square sections channels a reduction of the angle  $\alpha$  leads to the generation of more complex recirculation cells structures [10] that prevent the flow through the junction. Additional experiments were carried out to study the influence of the aspect ratio of the section of the channels. The results of these experiments are given in Table 1. The Fig.2 displays pictures of the experiments for  $\alpha = 30^\circ$  and 3 aspect ratio. For channels with a square cross section ( $Ar = 1.0$ , Fig.2a) none of the flow lines cross the junction. This is no more the case as the aspect ratio is reduced ; for instance for  $Ar = 0.14$  - Fig.2c - the fluorescent streamlines flowing throught the junction represent almost 6% of the total of its cross section. Experiments done with a constant aspect ratio but various angle  $\alpha$  demonstrate that the quantity of fluid flowing through the junction decreases with  $\alpha$ .

The Fig.3 shows the influence of the diffusion on the mixing of the fluids in the junction. For low Peclet number ( $=Uw/D_m$  where  $U$  and  $D_m = 2.10^{-10}\text{ m}^2/\text{s}$  are respectively the mean flow velocity and the molecular diffusion coefficient of the rhodamin), the frontier between the two fluids is less sharp than for highest Peclet number.

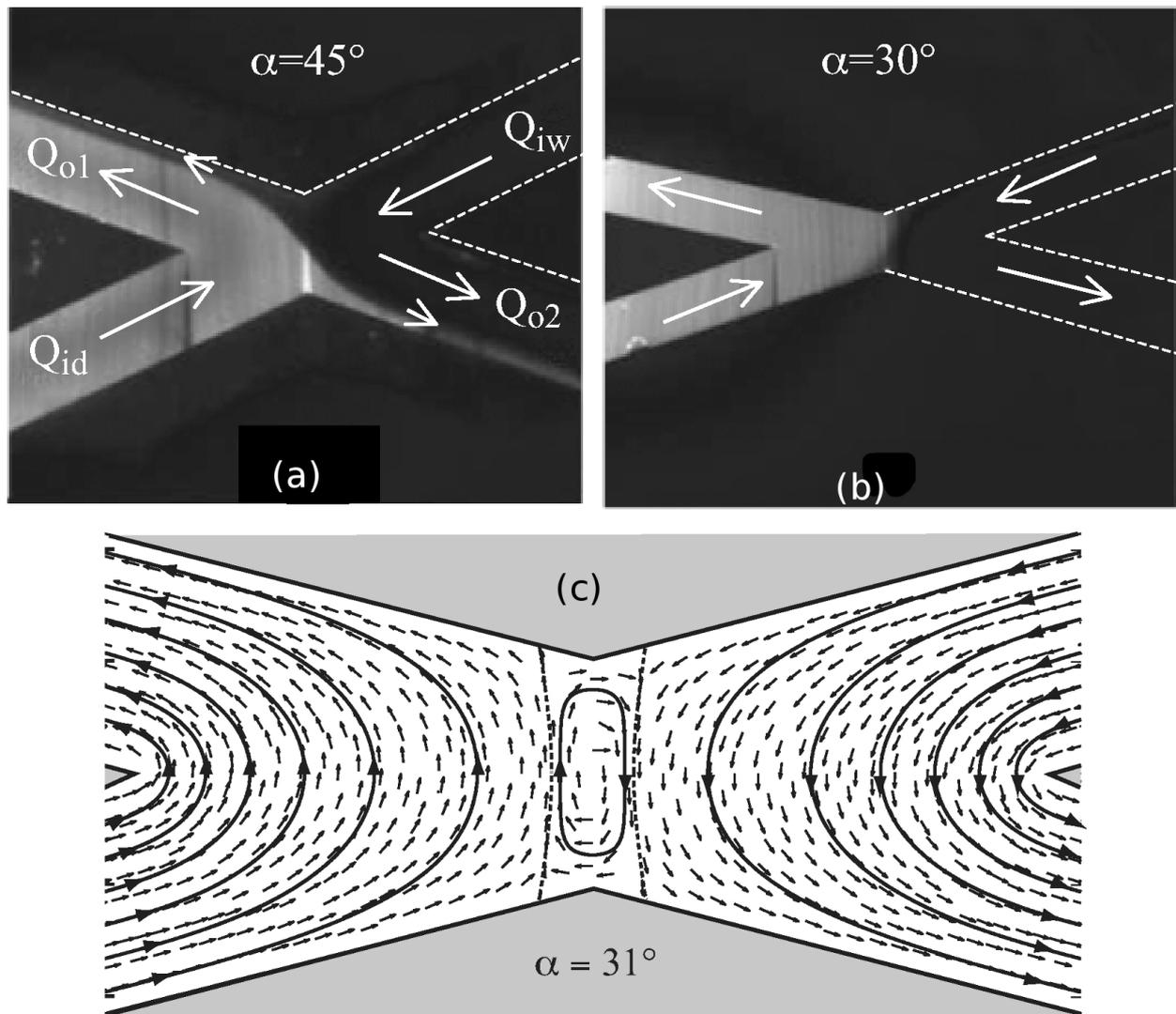


FIGURE 1 – (a) (b) experimental images showing the distribution of the fluids at the junction for (a)  $\alpha = 45^\circ$ ,  $Ar = 1.0$  and (b)  $\alpha = 30^\circ$ ,  $Ar = 1.0$ . (c) velocity field obtained numerically using FreeFem finite element package [11]. The continuous lines represent selected streamlines of the flow.

$\alpha$	Ar	w [mm]	h [mm]	$a_d/a$ (exp.)	$a_d/a$ (num.)
35°	0.56	3.55	2	$7.1 \pm 0.6$	4
	0.28	—	1	$7.7 \pm 1.6$	5.5
	0.28	1.73	0.5	$6.4 \pm 0.8$	5.5
	0.14	—	0.5	$8.4 \pm 1.8$	8
30°	1	3.55	3.55	0	0
	0.56	—	2	0	0
	0.28	—	1	$4.5 \pm 0.8$	4
	0.14	—	0.5	$6.3 \pm 0.8$	5
25°	0.56	3.55	2	0	0
	0.28	—	1	$3.55 \pm 1.1$	1.5
	0.14	—	0.5	$3.6 \pm 0.6$	3
25°	1	3.55	3.55	0	0
	0.14	—	0.5	$1.5 \pm 0.4$	1

TABLE 1 – Experimental and numerical observations.  $h$  and  $w$  are respectively the height and width of the channels and  $\alpha$  the crossing angle.  $Ar = h/w$  is the aspect ratio of the channels. (exp.) and (num.) refere respectively to the experimental and numerical evaluation of  $a_d/a$ .

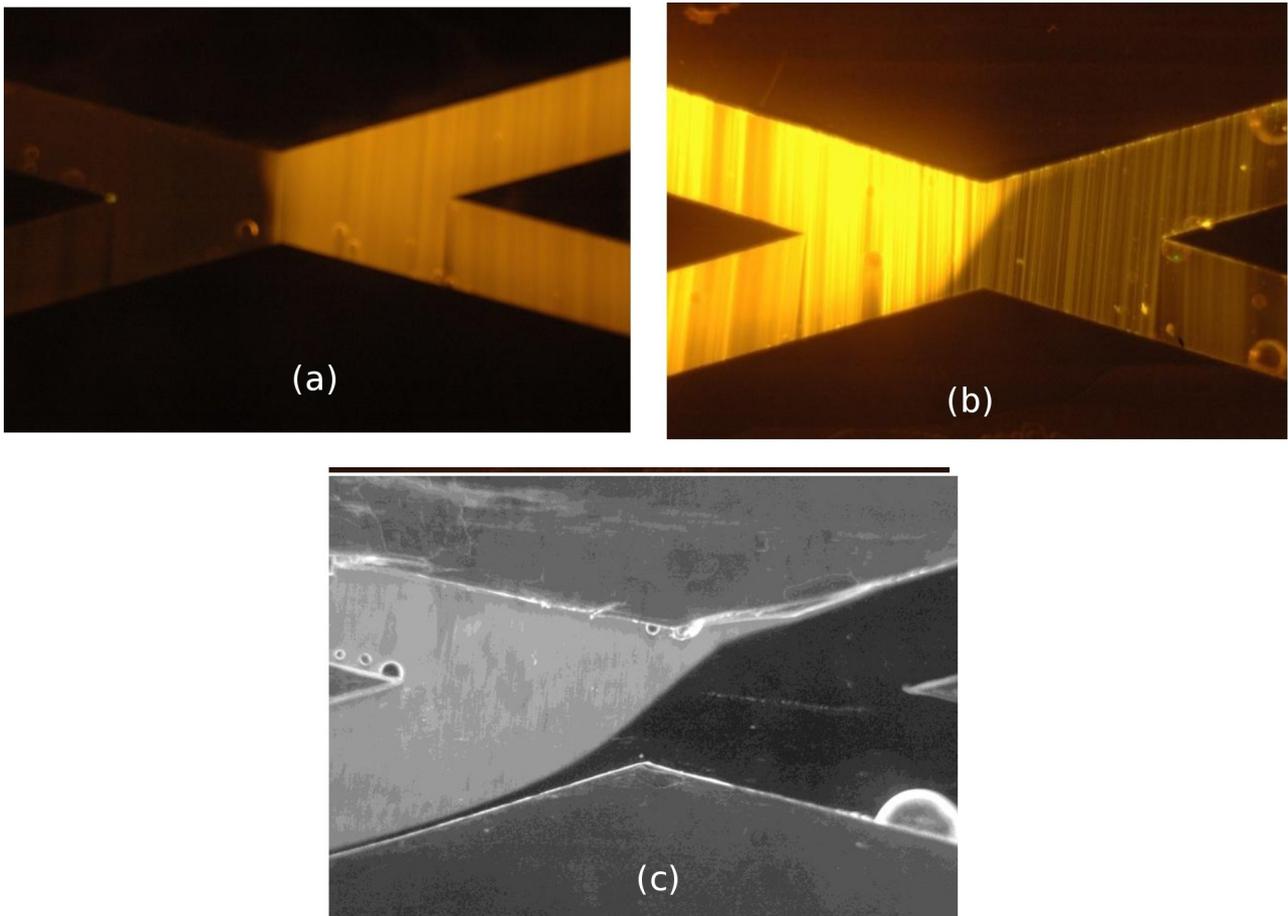


FIGURE 2 – From top to bottom, experimental pictures obtained for an angle  $\alpha = 30^\circ$  by for three aspect ratio  $Ar = 1.0, 0.57$  and  $0.14$ .

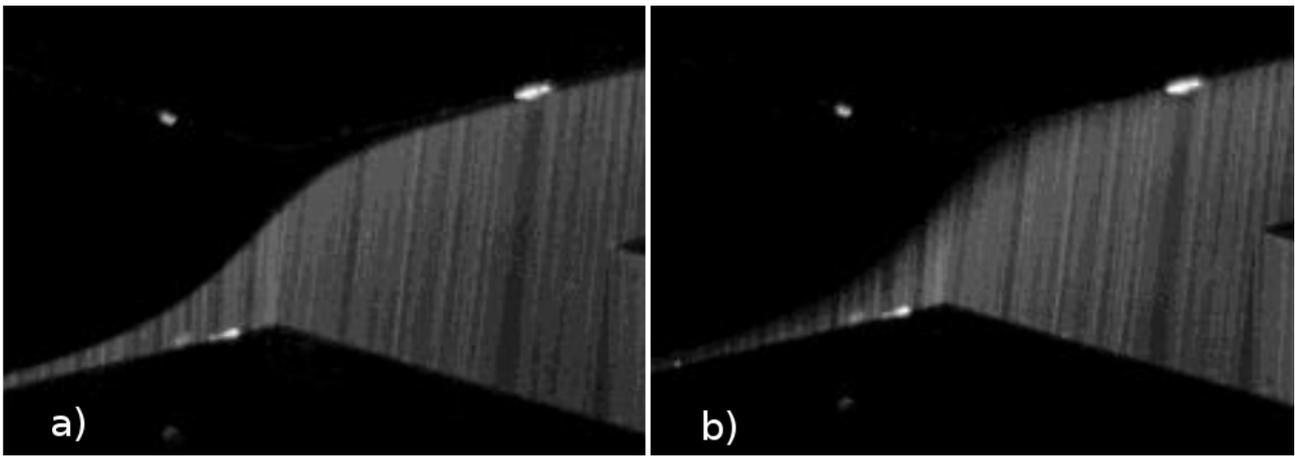


FIGURE 3 – View of the junction for  $\alpha = 35^\circ$  and  $Ar = 1.0$ . a)  $Pe = 10000$ . b)  $Pe = 600$

## 4 Discussion and Conclusions

The experiments and simulations presented here demonstrate that the recirculation cells appearing at low  $\alpha$  values will control the exchange of solute (or other passive or reactive species) between the two injected fluids : this exchange involves a combination of transverse molecular diffusion between the cells and the two flows (and from one cell to another) and convective transport by the circulation within the cells. We furthermore show that the aspect ratio of the channels influence the size of the recirculation cells. Reducing the aspect ratio reduces the size of the cells making possible to control the flow in the junction.

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