Desalination and Water Treatment
www.deswater.com
9 (2009) 253–258

Use of advanced CFD tool to characterize hydrodynamic of commercial UF membrane module

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Received 15 September 2008; Accepted 30 August 2009

ABSTRACT

The fouling and the clogging are the main reported issues in the ultrafiltration. If the raw water quality and membrane materials play an important role in the fouling, process design contributes significantly in the overall process performances. To improve the characterisation and the design of the membrane process, the computational fluid dynamics (CFD) modelling has been used to estimate the distribution of hydrodynamics values in the connection box and the UF module. The results of the CFD modelling indicate that the design of the module implies hydraulic path heterogeneities within the connection box mainly due to the permeate outlet, which creates vortex zones at the opposite side to the raw water inlet. However, these pressure heterogeneities would not impact membrane fouling since the pressure headlosses in the modules provide a pressure equilibrium along the fibers. Regarding the risk of clogging due to low recirculation velocity, only 2% of the fibers located in the vortex zones are concerned. In conclusion, this preliminary study proved the benefit of the CFD to validate the design of the module but this approach remains too global to include local interactions between the water and membrane material, which contribute to the fouling and consequently to the process performances.

Keywords: Membrane; Design; Modelling

1. Introduction

The use of membrane-based technologies in water treatment is the most important technological breakthrough of the last two decades. Introduced to the drinking water industry in early 1990s, low-pressure membrane processes, such as MF and UF, are today well recognized in the purification of potable but also for reclaimed and industrial waters. Both technologies present many advantages to conventional treatment processes including better and consistent final water quality, smaller footprint and lower operation and maintenance costs [1]. With a growth rate of approximately 15% per year since 2000, the number of commercial UF & MF products has significantly increased over the past 10 years with today 10 major players [2]. Whereas the technology is considered as mature, new applications and challenges are still emerging requiring persistent effort of all actors including more know-how, expertise and technological breakthrough in order to remain competitive in this active market.

Suez-Environment and its affiliates have been at the forefront of the membrane evolution from the very beginning—its first full-scale ultrafiltration plant started 20 years ago at Amoncourt in France—and continues to devote significant research means on the future of membrane to provide the best technology to customers. Thus, as example, Degrémont answered the reduction cost objectives by incremental evolution of its products design [3]. The recent evolution consisted to the development of a new product adapted to large plants including the new Ultrazur® 450 block system associated

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Presented at the Conference on Membranes in Drinking and Industrial Water Production, 20–24 October 2008, Toulouse, France.

to the new 450 module having a filtration surface area of 125 m². The Ultrazur® 450 was first installed for the Rouen project, a 24,000 m^3/d drinking water production plant located in France and more recently to the Moscow project to deliver up to 275,000 m^3 of water every day.

Although the membrane material appears as a key parameter of the system, the design of the module and the operation conditions of the process may also play an important role in the overall process performances [3]. If today, the pilot testing is still the principal method to evaluate the design and technology of the membrane processes, the information delivered is still global and cannot discriminate the impact of each component of the process such as the hydraulic behaviour within the module. To improve the characterisation and the design of the membrane process, the computational fluid dynamics (CFD) modelling appears as a relevant tool [4], which was already largely used in water industry [5].

The aim of this paper is to illustrate the use of the CFD to diagnostic the performance of a commercial ultrafiltration process used for drinking water applications. The specific objectives of the study were:

- Develop and optimise CFD model to characterise the hydrodynamic of UF module;
- Assess throughout experimental trials results of the CFD modelling;
- Evaluate the impact of the hydrodynamic on fouling propensity of the membrane module.

2. Material and methods

2.1. Ultrafiltration process

The membrane system considered in this study is designed by Degremont and uses pressurized ultrafiltration module from Degrémont Technologies-Aquasource operating with an inside/outside membrane configuration as presented in Fig. 1. This is a hollow fiber type membrane in cellulosic derivative with a pore size of 0.01 µm (molecular weight cut-off of 100 kD). The fibers (around 36,000) with an inside diameter of 0.9 mm are assembled in eight bundles and then placed inside a composite material module of 450 mm diameter, which is the largest module available in the market. The bundles are held together using resin, providing perfect and permanent sealing of the module, allowing a very high efficiency regards to viruses retention.

The bundles are distributed around the central collector in an "orange segment" shape. Module is mounted vertically between two headers (or connection boxes). The permeate is collected in the central collector and evacuated by the top of the module. The symmetrical position of the central collector in the 450 mm module allows a distribution improvement of the permeate flow inside the module and has been

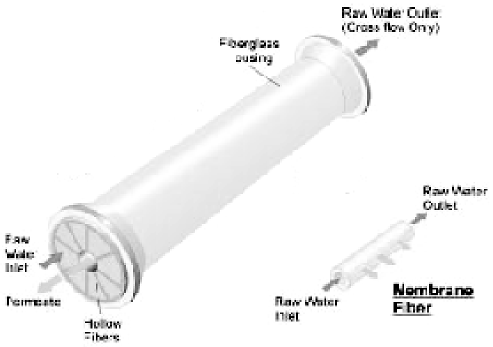

Fig. 1. Aquasource^{TM} membrane module.

optimized by computer modeling to improve the flow distribution along the fibers [3]. Raw water is fed by the off-center inlet of the upper connection box as illustrated in Fig. 2.

UF block, named Ultrazur® 450, comprises arrays of modules (16–24 modules per block) operating in parallel. The process depicted in Fig. 3 is capable of operating in either in dead-end or cross-flow mode. The majority of time, when raw water is low in suspended solids, the unit is operated in dead-end mode. When turbidity levels rise, operation can continue and cross-flow mode is automatically initiated. In cross-flow mode, powdered activated carbon (PAC) can be injected into the recirculation system. Proven for removal of organic matter, pesticides and other contaminants, PAC is also very effective for taste, color and odor control. In addition to optimizing the effectiveness of PAC injection, recirculation allows the ultrafiltration system to handle high turbidity spikes without a significant loss in throughput capacity.

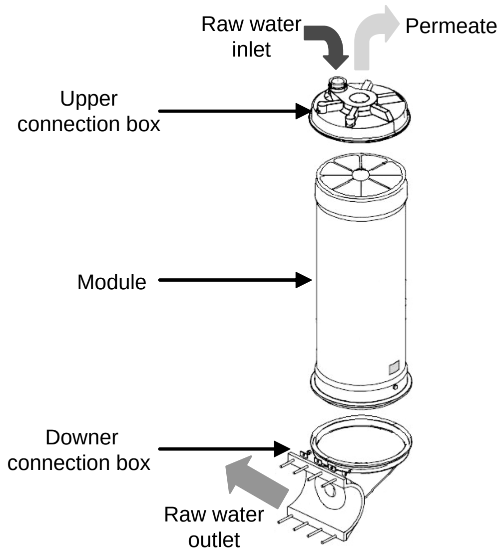

Fig. 2. Connection boxes.

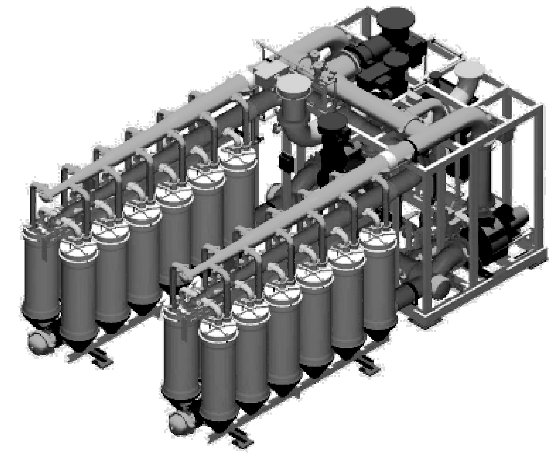

Fig. 3. Ultrazur® 450 unit equipped with 24 modules.

2.2. CFD methodology

The CFD study was divided in two parts:

1. Modeling of the flow in the upper header
   - Development of the CFD model and validation with experimental measures
   - Risk analysis on fouling and clogging behaviour
2. Modeling of the flow in the fibers
   - Development of the CFD model
   - Detailed analysis on fouling and clogging risks

The CFD simulations were carried out using the commercialized softwares Gambit v2.4.6 and Fluent v6.3.26.

2.2.1. Upper header meshgrid

The system symmetry was used to model only half of the module in order to reduce the size of the model. Also, to simplify the modelling of the 18,000 fibers requiring too much refinement and calculation capacity, the meshgrid of the upper header has been arbitrary created in 612 groups of fibers (one group for 29 fibers). These groups are sized in order to keep the intake section. The meshgrid illustrated in Fig. 4 contains four different boundary conditions:

- a velocity inlet condition to fix the inlet flow;
- a symmetry condition for the $y = 0$ plane;
- a outflow condition for the fibers entrance;
- a wall condition for the other boundary conditions.

The function used in Fluent was the "k-e realizable" due to the turbulent flow (Re ~ 250,000), and the similarity with jet on flat plate (i.e. inlet perpendicular to the module surface).

2.2.2. Module meshgrid

The meshgrid of the module has been designed in continuity of the upper header with 612 groups of fibres. Due to the reduction of the number of fibers, the membrane surface area from the model was not maintained. To consider this difference in the filtration flow calculation, a coefficient factor of 5.42 corresponding to quotient between the two membrane surfaces (125 m^2 as real/23 m^2 as simulated) as been used.

A source term corresponding to Hagen—Poiseuille law was added in the model to correct the pressure loss

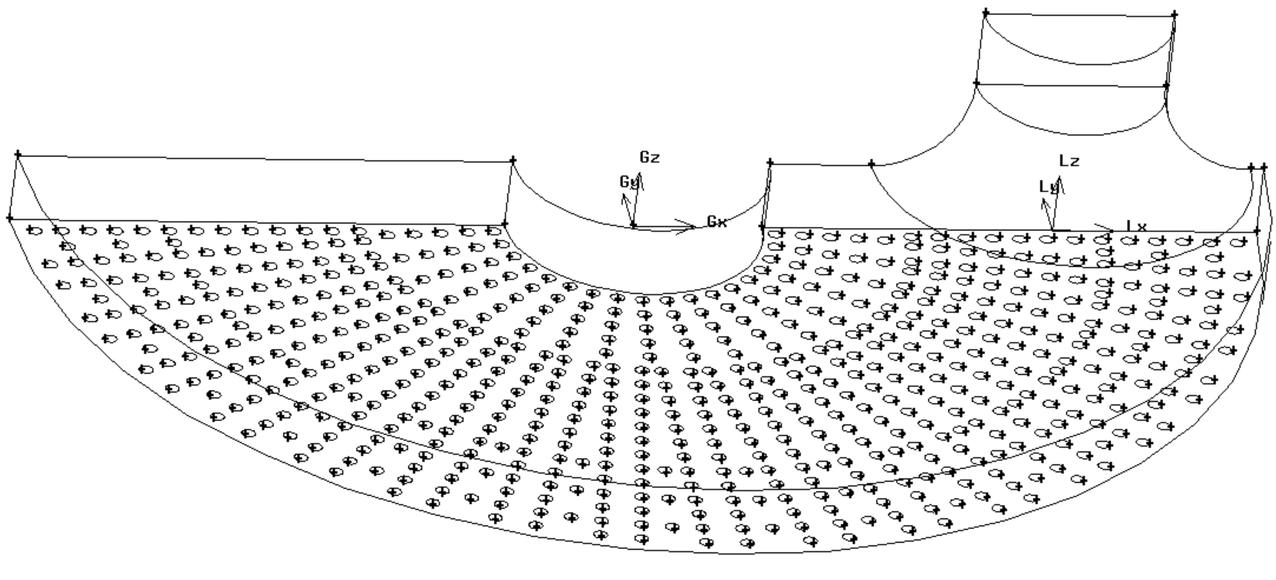

Fig. 4. Meshgrid of the upper hearder.

in the fibres. The meshgrid contains five different boundary conditions:

- a velocity inlet condition to fix the inlet flow;
- a velocity inlet condition to link the filtration flow with the internal pressure depending on the Darcy law;
- a symmetry condition for the $y = 0$ plane;
- a outflow condition for the outlet;
- a wall condition for the other boundary conditions.

2.3. Experimental set up

The numerical CFD model is based on assumptions to be checked, namely the expressions of the pressure headloss at the inlet of the fibre entry as well as the linear pressure headloss in fibre.

In order to validate the expression of the headloss at the inlet of the fiber, 16 pressure measurements were fixed on both upper and lower connection boxes to measure values ranged from 0 to 2.5 bars with an accuracy of 12.5 mbar. All the measurements were collected and stored in a PLC.

The implementation of the Pitot tubes as presented in Fig. 5 was based on the analysis of the first results provided by the CFD (streamlines). The objective of this experimental study was to validate the digital model.

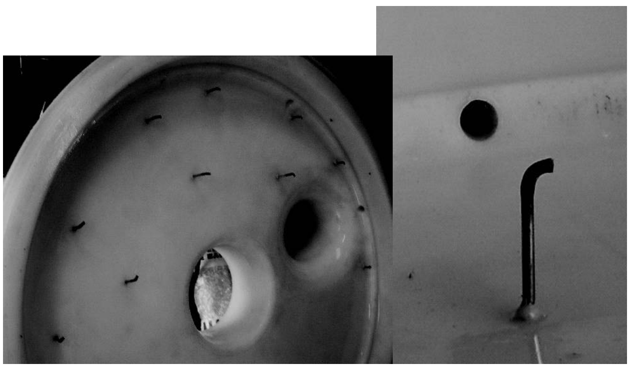

Fig. 5. Piot tube.

3. Results and discussion

3.1. Numerical solution

The CFD results of the upper connection box illustrated in Fig. 6 show that the design of the raw water inlet allow an overall good flow distribution in the upper connection box due to the high horizontal velocities located in zone 3.

However, the water is pushed towards the external wall of the upper connection box and create two vortex behind the permeate outlet. These two vortex zones (zone 2) present the minimum axial velocity and static pressure at the fiber inlet.

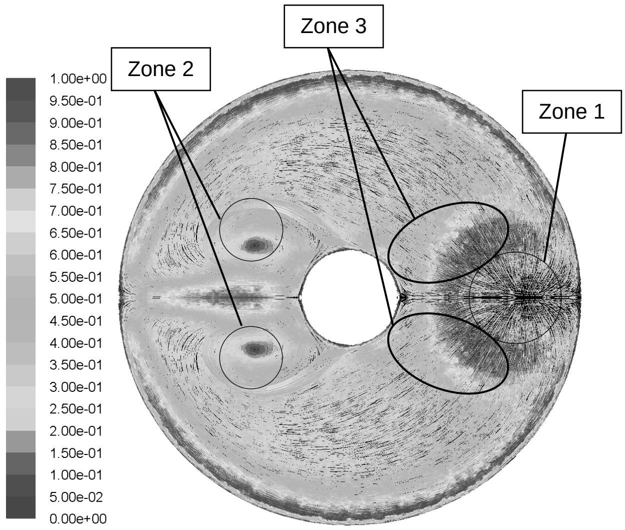

Fig. 6. Velociti es at z = 5 mm (m/s).

Underneath the raw water inlet (zone 1), the flow create high axial velocity and high static pressure at the inlet of the fibers. This phenomena impact approximately 8% of the total module fibers.

The pressure heterogeneities identified in the connection box should not impact the membrane fouling since the pressure headloss inside the modules reduce difference of pressures between the fibers. As illustrated in Fig. 7, this equilibrium implies that each fiber has the same permeate flux rate (less than 2.5 L/h/m² variation between the fibers). Regarding the risk of clogging, only 2% of the fibers located in the vortex zones are concerned. In fact, the velocity heterogeneities observed at the top of the module are conserved at the bottom as shown in Fig. 8.

It was clearly noticed that the filtration flux decreases along the fibers because of the pressure headlosses. Consequently, the fouling risk is higher in the upper part of the module. Also, due to the filtration, the recirculation velocity decrease along the fibers, which cause higher clogging risk in the lower part of the module. This risk is however not homogeneous because of the conservation of velocity heterogeneities due to the same production of each fiber.

3.2. Calibration

The numerical results of total pressure were compared to the experimental measures in the Fig. 9. The discrepancy between the maximal and minimal pressure is underestimated by the CFD (64 mbar for the experimental results and 30 mbar for the numerical results). This difference can be explained by the accuracy of the pressure sensors and model hypothesis. The small difference between p1-e01 and p1-e06 validates

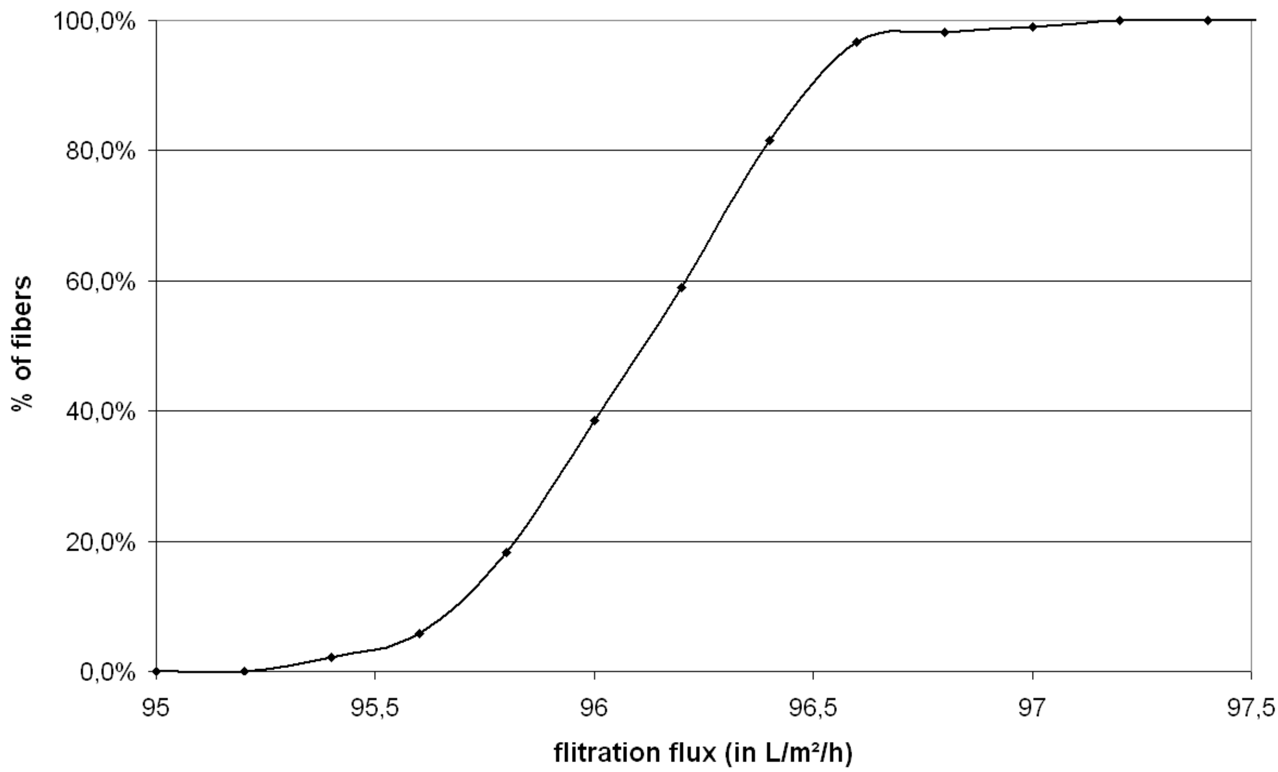

Fig. 7. Filtration flux distribution at z = 1 m.

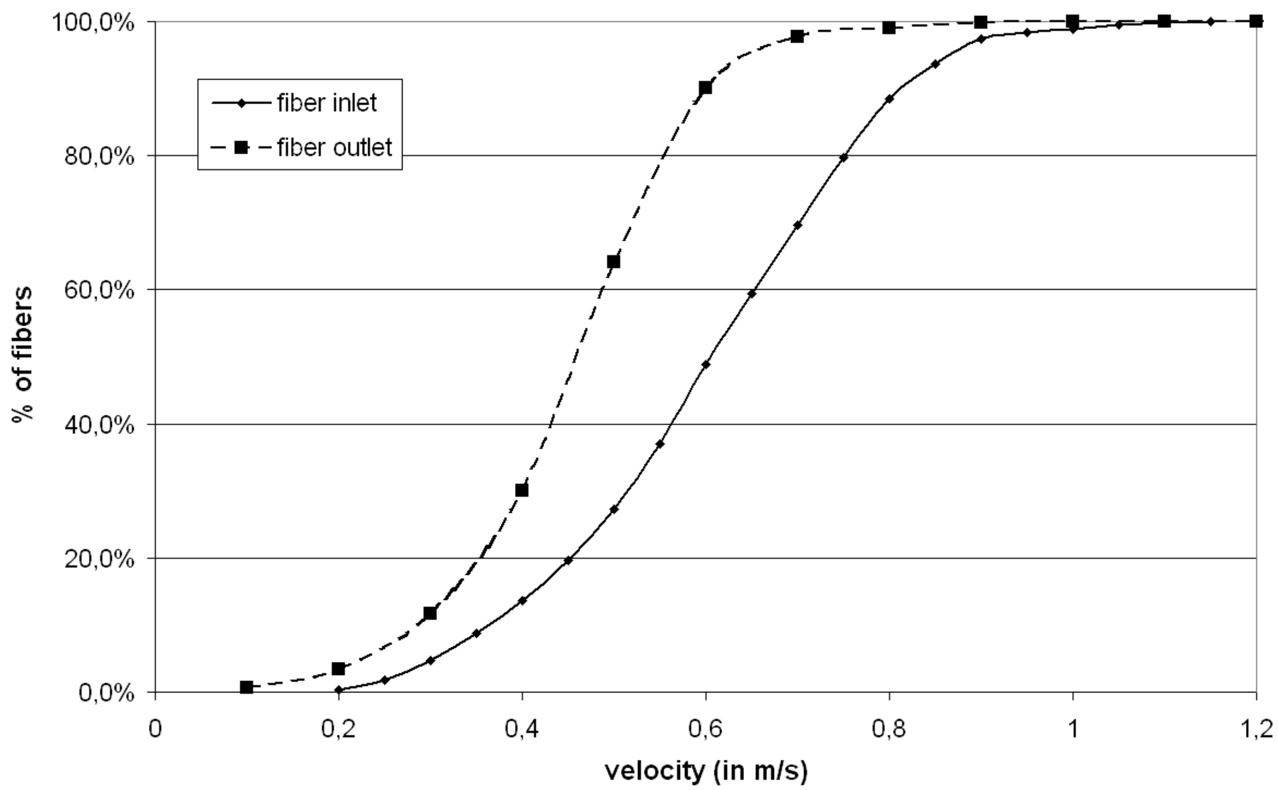

Fig. 8. Velocity distributions at the inlet and the outlet of fibers.

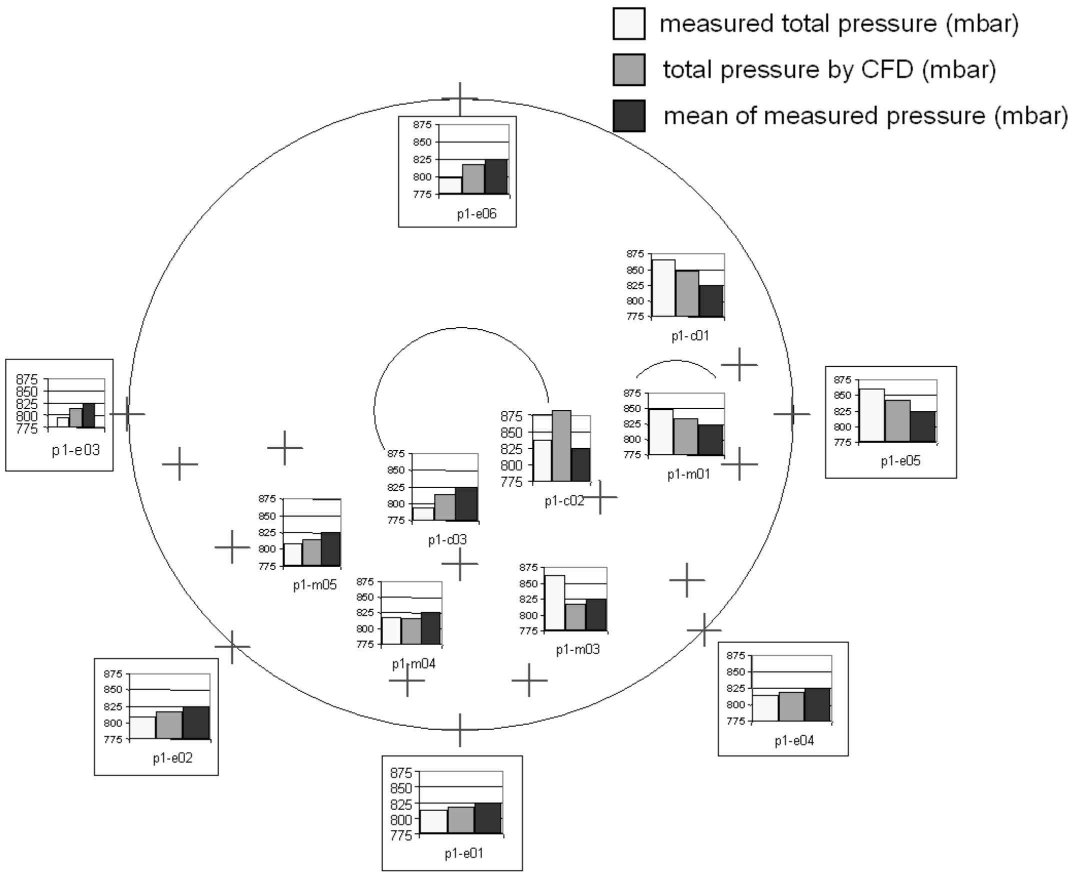

Fig. 9. Comparison between the numerical and experimental pressure results.

the use of the symmetry. Overall, the pressure variations are well simulated by the CFD.

4. Conclusion and perspectives

The results of the CFD modelling indicate that the design of the module implies hydraulic path heterogeneities within the connection box of the module mainly due to the permeate outlet, which creates vortex zones at the opposite side to the inlet. However, these pressure heterogeneities would not impact membrane fouling since headlosses in the modules provide pressure equilibrium along the fibers. The highest pressure is observed underneath the raw water inlet and concerns up to 10% of the fibers. Regarding the risk of clogging due to low recirculation velocity, only 2% of the fibers located in the vortex zones are concerned.

In conclusion, this preliminary study proved the benefit of the CFD to validate the design of the module but this approach remains too global to include local interactions between the water and membrane material which contribute to the fouling and consequently to the process performances.

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