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Numerical Investigation of the Effect of Blower Baffles on the Performance of Membrane Tubes for Water Treatment

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Abstract: Effects of blower shaped baffles on the fluid dynamics and filtration flux in a membrane tube are numerically explored. Both the staggered and inline arrangements of baffles are studied. The carbonate calcium suspensions with a concentration of 5 g/L were used as a working medium. The efficiency of filtration was determined via the calculation of velocity of fluid particles, wall shear stresses and static pressure. An increase in the shear stresses on the tube surface, as well as a formation of fluid eddies were observed with the presence an array of blower baffles, resulting thus in a significant improvement of the filtration performance. The case of the staggered baffles with pith ratio of L/D = 1 and Re = 15,000 achieved an increase in the filtration flux rate by 42% and 12%, compared with unbaffled and tube with baffle orientation angle of 180°, respectively.

Keywords: Membrane tube; cross-flow; filtration; water treatment; performance of membrane.

1. Introduction

The membrane tubes are important equipment employed in water treatment systems and other industrial fields concerned with separation and purification technology [1-3]. However, the problems of fouling and concentration polarization generate a hydrodynamic boundary layer near the membrane walls and yield a reduction of the filtration flux [4-8].

The nature of fluids and their physical properties, as well as the design of the membrane system play a major role on the formation of cake layer near the membrane walls [9-11]. In addition, the acceleration of membrane fouling may be the result of the lack of sufficient shear stress on the membrane wall, which reduces significantly the filtration flux [12-14]. Recently, a very promising technique to improve the solute mass transfer is using baffles known as turbulence developers or vortex generators inside the membrane system. These baffles allow changes in the flow patterns and reduce the development of hydrodynamic boundary layer, which enhances by consequence the filtration flux. Various designs have been proposed by many researchers in order to develop the mass transfer in membrane tubes [14-16]. Among the different strategies used by means of experiments [17-21], the filtration flux is augmented for two main effects: the change of hydrodynamic structure and augmentation of wall shear stress on membrane surface.

The CFD (computational fluid dynamic) method is becoming nowadays a very suitable tool in the knowledge field of membrane system, due to development of numerical methods and machine computers. The CFD method allows obtaining

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adequate results in less time and with less expense of energy [22-26]. Monfared et al. [27] investigated the effect of presence of baffles in the membrane tube by using the CFD method and they found a considerable enhancement in the filtration performances. Rainer et al. [28] explored by numerical simulations the effect of the presence of rotating discs inside the membrane tube and they obtained a significant augmentation of the filtration execution. Ameur and Sahel [29] inserted hemispherical baffles in a membrane tube and explored numerically the effect of their arrangements (right and left orientations, RO and LO, respectively). Their results revealed the superiority of LO baffle than the other case, where the filtration flux was increased by about 96% for 10 g/L of feed concentration of carbonate calcium, compared with unbaffled tube.

The influence of baffle orientation angles as well as the diameter ratio was the subject of a numerical study conducted by Jafarkhani et al. [30]. The best filtration flux has been obtained with the case of 180° of baffle orientation, due to the intensification of shear stress, fluid velocity and solute mass transfer on the membrane surface.

In the present paper, the effect of new shaped baffles on the performance of membrane tubes is explored via the CFD method. An array of blower baffles is inserted in the tube under turbulent flow conditions. Effects of the baffle arrangements and their pitch on the flow structures, wall shear stresses, mass flux and pressure drops are the main parameters under investigation.

2. Material and method

The geometrical configuration of the present study is a horizontal tube with length (L) of 0.2 m and inner diameter (D) of 0.015 m (Fig.1). The thickness of baffle (b_t) is 1 mm and its size (d) is set to $D/2$. The first baffle is located at a distance of 0.022 m from the inlet tube and the spacing between baffles (l) is equal to 0.0225 m. Effects of in-line and staggered arrangements of blower baffles were tested.

3. Mathematical tools

The continuity and Reynolds averaged Navier–Stokes equations for a Newtonian, incompressible and isothermal fluid, with constant physical properties (water) in a tubular membrane are given

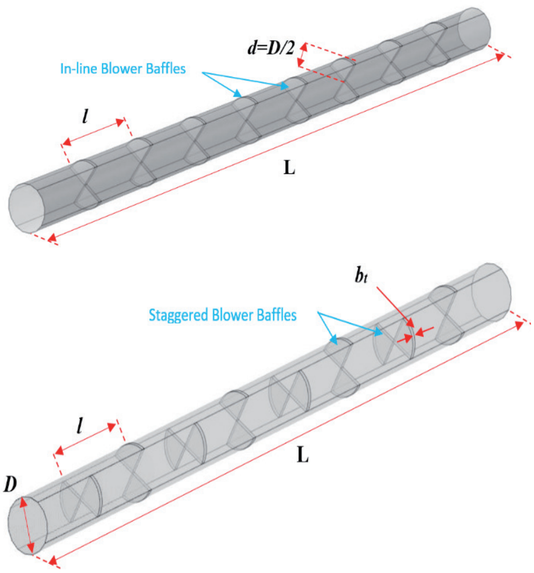

Fig. 1 Configurations of baffled tubes.

as follows:

Mass conservation:

$$\frac{\partial \tilde{n}}{\partial t}+\frac{\partial}{\partial x_i}(\tilde{n} u_i)=0 \tag{1}$$

Momentum equation:

$$\frac{\partial \tilde{n} u_i}{\partial t}+\frac{\partial}{\partial x_j}(\tilde{n} u_i u_j)=$$
$$=\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\left(\frac{2}{3}\mu\frac{\partial u_i}{\partial x_i}\right)\right]-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$

The Reynolds-averaged method to turbulence modeling includes the modeling of the Reynolds stresses $-\rho\overline{u_i' u_j'}$ in Eq. (2). The Boussinesq hypothesis relates the Reynolds stresses to the mean velocity gradients as present in the following equation:

$$-\rho\overline{u_i' u_j'}=\mu_t\left(\frac{\partial u_i}{\partial x_i}+\frac{\partial u_i}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+\mu_t\frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \tag{3}$$

The turbulent viscosity (μ_t) is described by:

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon},\quad C_\mu=0.085 \tag{4}$$

where, k is the turbulent kinetic energy, ε is the turbulent dissipation rate, $C_\mu = 0.085$ is the constant in $k-\varepsilon$ equations.

The Reynolds number is defined as:

$$\mathrm{Re} = \rho U_m D_h / \mu \tag{5}$$

where, ρ is the density of water, Um is the velocity in the inlet section, Dh is the hydraulic diameter, and μ is the kinetic viscosity of water.

In order to close the equations system, the *RNG* $k-\varepsilon$ is the advised model to predict turbulent flow baffled ducts [25]. The *RNG* $k-\varepsilon$ turbulence model is derived from the instantaneous Navier-Stokes equations, where the "renormalization group" *(RNG)* is the mathematical technique methods is used for this approach.

The filtration flux is defined by Darcy's equation [18, 25, and 28]:

$$j = {TMP}\Big/{\mu\left(R_m + R_c\right)} \tag{6}$$

where, Rm and *TMP* are the clean membrane resistance and the trans-membrane pressure, respectively. In the present simulation, a single phase was considered and the cake resistance Rc was neglected. As the effect of membrane compression was neglected, the value Rm = 2.10^{10} $1/\mathrm{m}$ was employed to studying the flow behavior [25, 30]. For unsteady simulation, we can compute the filtration flux according to the time of filtration, where the time step is set to 0.01 s.

4. Numerical details

Investigations were realized with the assist of the computer software ANSYS Fluent. The inlet velocity and outlet pressure were respectively set to 0.5 m/s $(Re = 7500)$ and 50 kPa for all case studied here. No effect of wall suction on the flow characteristics was considered, since the filtration rate in membrane systems is usually less than 0.5% of the total cross-flow velocity. Moreover, no-slip wall and impermeable boundary conditions were employed, as used by many researchers [25, 31, and 36].

The different computational domains were meshed by triangular grid elements via the Gambit Software. After mesh tests, the less expensive mesh size with no additional changes than 2.5% in the filtration flux, had about 880,000 elements. The finite volume method was used to solve the governing equations. The first-order upwind numerical scheme was adopted for the discretization of equations and the SIMPLE algorithm is used to perform the pressure-velocity coupling. Under the default under-relaxation factors of the Fluent software, the residual target of 10^{-7} was considered as a criterion of convergence. With a machine having Core i7 CPU 2.20 GHz with 8.0 GB of RAM, the calculations required about 15 hours of CPU time.

5. Results and discussion

The validity of our numerical model and boundary conditions is checked at the first stage of our study. For this purpose, we based on the works of Liu et al. [25] and Jafarkhani et al. [30] and we constructed the identical geometrical conditions. The calcium carbonate suspensions with a mean particle size of 7.96 μm were used as a working medium, where the trans-membrane pressure (TMP) was set to 50 kPa and the inlet velocity was equal to 0.5 m/s $(Re = 7500)$. Fig. 2 shows the variations of filtration flux vs. the filtration time, for Carbonate calcium at 5 g/l. The comparison is made for tube without baffles and tubes with baffle orientation angle of 1800. The comparison between our numerical results and the experimental data of Liu et al. [25] and Jafarkhani et al. [30] shows a good agreement.

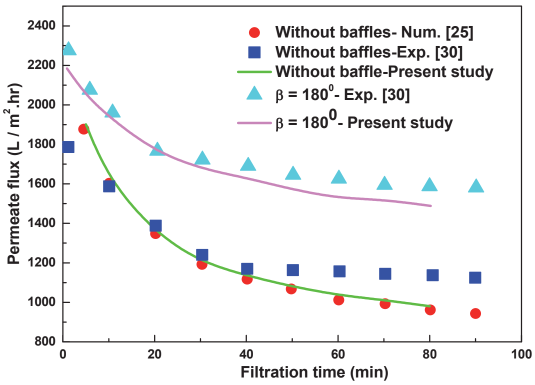

Figure 2: Filtration flux vs. filtration time for TMP = 50 kPa and 5g/l for carbonate calcium.

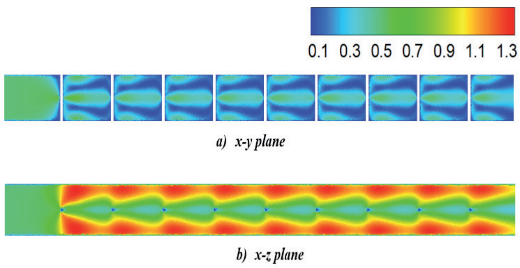

Figure 3: Axial velocity contours, for in-line blower baffles.

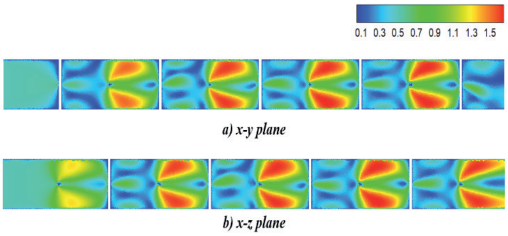

Figure 4? Axial velocity contours, for staggered blower baffles.

5.1. Flow fields

It is well known that the reduction of the filtration flux may be mainly caused by the build-up of the hydrodynamics boundary layer, which is observed in smooth membrane tubes. For this reason, many efforts have been made by researchers to enhance the performance of such systems by introducing several kinds of baffles (for example, see [32-37]).

This study shows the development of flow patterns when blower baffles are inserted in the membrane tube. Figs. 3 and 4 illustrate the contours of flow distribution for $Re = 7500$. In the unbaffled membrane tube, the particles of fluid are more prone to deposit on the membrane surfaces to form a thick layer, however, the fluid flow is fully turbulent in the membrane tube equipped with in-line and staggered blower baffles. The formation of hydrodynamic boundary layer is reduced and the velocity fluctuations are increased in the baffled tube, resulting thus in a reduction of concentration polarization and membrane fouling, and enhanced performance of the system.

5.2. Wall shear stress

In the conception of efficient industrial membrane systems, the intensification of velocity fluctuations and shear stresses on the membrane walls is required. For inline and staggered configurations of blower baffles, variations of the wall shear stress vs. Reynolds numbers are presented in Fig. 5. This figure illustrates clearly that the rise of Reynolds numbers augments the wall shear stress and as a result, it augments the fluctuation of velocity and decreases the suspension of fluid particles on the membrane walls.

The highest values of (WSS) are remarked for chief value of Reynolds number ($Re = 1500$). Where, for inline and staggered arrangements of baffles, the maximum, values are 58 Pa and 74 Pa respectively. Hence, the staggered blower baffles present the better choice to generate the highest values of wall shear stress in the membrane surface.

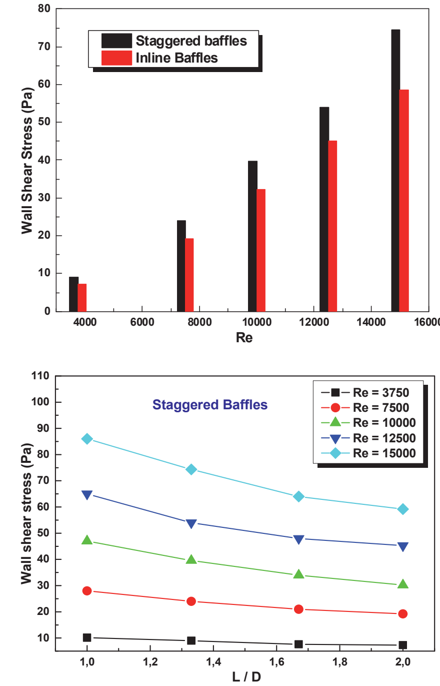

Figure 5: Wall shear stress versus (a) Re and (b) L/D.

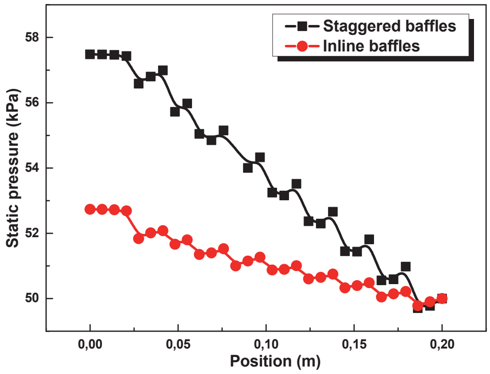

Figure 6: Pressure drop along the tubes.

Therefore, it is necessary to optimize the better configuration that is used to design the membrane system. Therefore, the effect of the spacing between baffles or (baffles pitch ratio, *L/D*) is also analyzed in this section. Fig. 6 shows the evolution of the wall shear stress versus different values of pitch ratios. This figure illustrates that the augmentation of the baffle pitch ratio decreases the generation of the wall shear stress due to the diminution of the vortex intensity between of two successive baffles. As a remark, the minimum value of pitch ratio ($L/D = 1$) presents the maximum value of wall shear stress

(86 Pa), at the highest Reynolds numbers value ($Re = 15{,}000$).

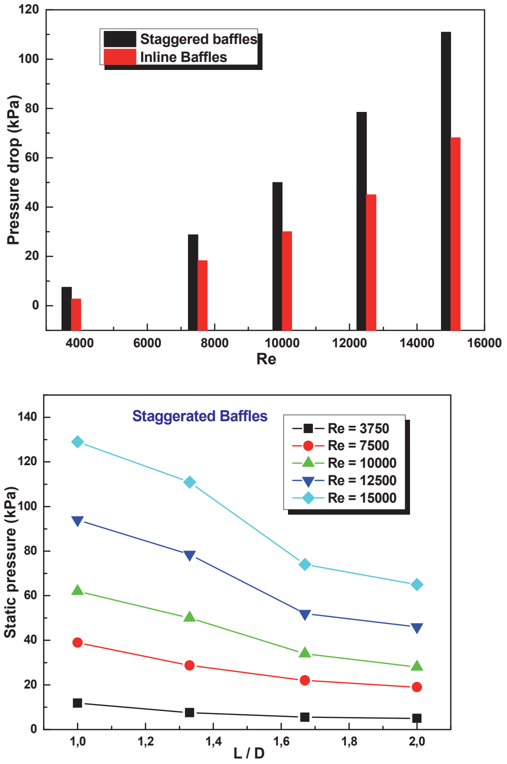

Figure 7: Pressure drop versus (a) Re and (b) L/D.

5.3. Static pressure

For $Re = 7500$, Fig. 6 reveals the variation of static pressure for two configurations. The pressure losses along the membrane tube are approximately 57.5 and 52.8 kPa for the staggered and inline blower baffles arrangement, respectively. The highest pressure drops values for the staggered configuration are due to the deviation and the change of the flow direction inside the tube. This increase of pressure losses yields an additional energy cost of the system.

Fig. 7(a) presents the pressure drop variation versus Reynolds number value for two configurations. The figure shows clearly that the pressure drop increase in the rise of the Reynolds number values for staggered and inline arrangements. Then, the staggered blower baffles generate maximum values of pressure drop.

Hence, it is necessary to adjust the better arrangement that is used to design the membrane system. Therefore, the effect of the baffle's escapement or (baffles pitch ratio, L/D) is also analyzed in this section.

Fig. 7(b) shows the distribution of the pressure versus different values of pitch ratios. This figure depicts that the increases of the baffle pitch ratio decline the pressure losses due to the diminution of the turbulence intensity between of two successive baffles. As a remark, the minimum value of pitch ratio ($L/D = 1$) present the maximum value of pressure drop (130 Pa), at the highest Reynolds numbers value ($Re = 15{,}000$).

5.4. Optimization of the staggered configuration of baffles

The space between two successive baffles influences directly the behavior of the filtration flux in a membrane tube. Hence, it is necessary to study the effect of this geometrical parameter in the presence of the blower baffle shape as a new concept in this paper.

As we discussed above, the pitch ratio (L/D) or the space between two successive baffles influence directly on the wall shear stress and pressure drop. For an interval of ($L/D = 1$ to 2), each the (WSS) and pressure drop tend to decrease in the rise of the pitch ratio (L/D), for all Reynolds number values. Therefore, the smallest value of pitch ratio ($L/D = 1$) and the highest Reynolds number ($Re = 15{,}000$) create the peak values of wall shear stress and pressure drop, which are 86 Pa and 130 Pa, respectively.

As discussed above, the staggered baffles create the highest values of (WSS) and pressure drop. Therefore, these configurations ensure a better filtration time. For the baffle pitch ratio (L/D) of 1, variations of the filtration flux according to the filtration time are given in Fig. 8.

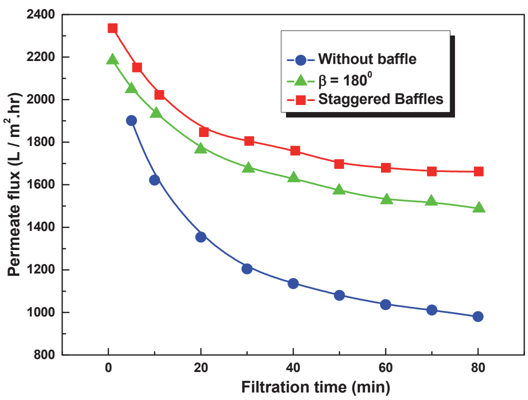

Figure 8: Filtration flux vs. filtration time for TMP = 50 kPa and 5g/l of carbonate calcium.

From the figure, analysis of numerical results expose that the staggered baffles produce a high steady state flux than the unbaffled membrane and membrane of baffle orientation angle of 180°, with an increase by 42% (than that unbaffled tubes) and 12 % (than that baffle orientation angle of 180°) at the feed concentration of 5 g/L.

6. Conclusion

The turbulent flow in a baffled membrane tube with staggered and inline arrangements of baffles were investigated using CFD Ansys FLUENT software. The velocities, wall shear stresses, static pressure are physical parameters were used to predict the turbulent flow characteristics for unbaffled tube, staggered and inline baffles.

The filtration flux was evaluated by using the shearing force as a primordial parameter. The numerical results exhibited an intensification of velocity fluctuations and shear stresses in the membrane tube with the presence of an array of staggered blower baffles. The strong changes in flow direction and eddies generated behind each baffle are responsible of the enhancement of the filtration flux.

The case of the staggered baffles with $L/D = 1$ and $Re = 15{,}000$ produces the maximum values of wall shear stresses (*WSS*) and gives the greatest filtration flux rate compared with unbaffled tube and others types of baffled membranes existing in the literature.

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