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

Djamel Sahel ^{1,*}, Warda Boudaoud ², Houari Ameur ³, Karima Alem ²

¹ Department of Technical Sciences, University Amar Telidji of Laghouat, Algeria

² Faculty of Mechanical Engineering, USTO-MB, Oran, Algeria

³ Department of Technology, University Centre of Naama, P.O. Box 66, Naama 45000, Algeria

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 un baffled 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

* Corresponding author: Djamel Sahel, *E-mail address:* d.sahel@lagh-univ.dz

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. Ameer 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:

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

Momentum equation:

$$\begin{aligned} \frac{\partial \tilde{n} u_i}{\partial t} + \frac{\partial}{\partial x_j} (\tilde{n} u_i u_j) = \\ = \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \left(\frac{2}{3} \mu \frac{\partial u_i}{\partial x_i} \right) \right] - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} (-\rho \overline{u_i u_j}) \end{aligned} \quad (2)$$

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:

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

The turbulent viscosity (μ_t) is described by:

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

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:

$$Re = \rho U_m D_h / \mu \quad (5)$$

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

In order to close the equations system, the *RNG* $k-\epsilon$ is the advised model to predict turbulent flow baffled ducts [25]. The *RNG* $k-\epsilon$ 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]:

$$j = \frac{TMP}{\mu (R_m + R_c)} \quad (6)$$

where, R_m 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 R_c was neglected. As the effect of membrane compression was neglected, the value $R_m = 2.10^{10} \text{ 1/m}$ 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 inline 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.

References

- [1] Bick, A., Yang, F., Shandalov, S., Raveh, A., Oron, G., (2011). Multi-Dimension scaling as an exploratory tool in the analysis of an immersed membrane bioreactor, *Membrane Water Treatment*, 2, 105-119.
- [2] Guo, J., Liu, J.H., Wang, L., Liu, H., (2015). Modification of ultrafiltration membranes with carbon nanotube bucky paper for fouling alleviation, *Membrane Water Treatment*, 6, 1-13.
- [3] Kim, S.H., Lee, T.M., (2016). Performance improvement of membrane distillation using carbon nanotubes, *Membrane Water Treatment*, 7, 367-677.
- [4] Haan, T.Y., Shah, M., Chun, H.K., Mohammad, A.W., (2018). A study on membrane technology for surface water treatment: Synthesis, characterization and performance test, *Membrane Water Treatment*, 9, 69-77.
- [5] Kumar, K., De, S., (2010). Modeling of flux enhancement in presence of concentration polarization by pressure pulsation during laminar cross flow ultrafiltration, *Membrane Water Treatment*, 1, 253-271.
- [6] Tian, H., Sun, L., Duan, X., Chen, X., Yu, T., Feng, C., (2018). Pre-deposition of iron-based adsorbents on the removal of humic acid using ultrafiltration and membrane fouling, *Membrane Water Treatment*, 9, 473-480.
- [7] Jhaveri, J.H. Patel, C.M., Murthy, Z.V.P., (2018). Reactive modification of PVC membranes for the improved performance, *Membrane Water Treatment*, 9, 385-392.
- [8] Sarihan, A., Eren, E., (2017). Novel high performed and fouling resistant PSf/ZnO membranes for water treatment, *Membrane Water Treatment*, 8, 563-574.
- [9] Gupta, B.B., Howell, J.A., Wu, D. Field, R.W., (1995). A helical baffle for cross flow micro filtration, *Journal of Membrane Sciences*, 99, 31-42.
- [10] Krstic, D.M., Koris, A.K., Tekica, M.N., (2006). Dostatic turbulence promoters have potential in cross-flow membrane filtration applications, *Desalination*, 191, 371-375.
- [11] Krstic, D.M., Tekic, M.N., Caric, M.D., Milanovic, S.D., (2004). Static turbulence promoter in cross-flow microfiltration of skim milk, *Desalination*, 163, 297-309.
- [12] Ghaffour, N., Jassim, R., Khir, T., (2004). Flux enhancement by using helical baffles in ultrafiltration of suspended Solids, *Desalination*, 167, 201-207.
- [13] Hadzismajlovic, D.E., Bertram, C.D., (1999). Flux enhancement in turbulent cross flow microfiltration of yeast using a collapsible-tube pulsation generator, *Journal of Membrane Sciences*, 163, 123-134.
- [14] Pal, S., Bharihoke, R., Chakraborty, S., Ghatak, S.K., De, S., Gupta, S.D., (2008). An experimental and theoretical analysis of turbulence promoter assisted ultrafiltration of synthetic fruit juice, *Separation and Purification Technology*, 62, 659-667.
- [15] Chen, W.H., Lin, C.H., Lin, Y.L., (2014). Flow-field design for improving hydrogen recovery in a palladium membrane tube, *Journal of Membrane Sciences*, 472, 45-54.
- [16] McDonough, J.R., Phan, A.N., Harvey, A.P., (2015). Rapid process development using oscillatory baffled mesoreactors – A state-of-the-art review, *Chemical Engineering Journal*, 265, 110-121.
- [17] Finnigan, S.M., Howell, J.A., (1989). The effect of pulsatile flow on ultrafiltration fluxes in a baffled tubular membrane system, *Chemical Engineering Research and Design*, 67, 278-282.
- [18] Mackley, M.E., Mackley, M.R., Wang, Y., (1991). Oscillatory flow within tubes containing wall or central baffles, *Chemical Engineering Research and Design*, 69, 506-513.
- [19] Mackley, M.R., Twedde, G.M., Wyatt, I.D., (1990). Experimental

- heat transfer measurements for pulsatile flow in baffled tubes, *Chemical Engineering Sciences*, 45, 1237-1242.
- [20] Brunold, C.R., Hunns, J.C.B., Mackley, M.R., Thompson, J.W., (1989). Experimental observation on flow patterns and energy losses for oscillatory flow in ducts containing sharp edges, *Chemical Engineering Sciences*, 44, 1227-1244.
 - [21] Wang, L., Wu, Z., Zhao, B., Liu, W., Gao, Y., (2013). Enhancing the adsorption of the proteins in the soy whey wastewater using foam separation column fitted with internal baffles, *Journal of Food Engineering*, 119, 377-384.
 - [22] Wang, Y.Y., Howell, J.A., Field, R.W., Wu, D.X., (1994). Simulation of cross-flow for baffled tubular channels and pulsatile flow, *Journal of Membrane Sciences*, 95, 243-258.
 - [23] Liu, X., Wang, Y., Waite, T.D., Leslie, G., (2015). Numerical simulation of bubble induced shear in membrane bioreactors: Effects of mixed liquor rheology and membrane configuration, *Water Research*, 75, 131-145.
 - [24] Chen, W.H., Syu, W.Z., Hung, C.I., Lin, Y.L., Yang, C.C., (2013). Influences of geometry and flow pattern on hydrogen separation in a Pd-based membrane tube, *International Journal of Hydrogen Energy*, 38, 1145-1156.
 - [25] Liu, Y., He, G., Liu, X., Xiao, G. and Li, B., (2009). CFD simulations of turbulent flow in baffle-filled membrane tubes, *Separation and Purification Technology*, 67, 14-20.
 - [26] Ahmed, S., Seraji, M.T., Jahedi, J., Hashib, M.A., (2011). CFD simulation of turbulence promoters in a tubular membrane channel, *Desalination*, 276, 191-198.
 - [27] Monfared, M.A., Kasiri, N., Salahi, A., Mohammadi, T., (2012). CFD simulation of baffles arrangement for gelatin-water ultrafiltration in rectangular channel, *Desalination*, 284, 288-296.
 - [28] Rainer, M., Hoflinger, W., Koch, W., Pongratz, E., Oechsle, D., (2002). 3D-flow simulation and optimization of a cross flow filtration with rotating discs, *Separation and Purification Technology*, 26, 121-131.
 - [29] Ameer, H., Sahel, D., (2017). Effect of baffle design and orientation on the performance of a membrane tube, *Chemical Engineering Research and Design*, 117, 500-508.
 - [30] Jafarkhani, M., Moraveji, M.K., Davarnejad, R., Moztarzadeh, F., Mozafari, M., (2012). Three-dimensional simulation of turbulent flow in a membrane tube filled with semi-circular baffles, *Desalination*, 294, 8-16.
 - [31] Koutsou, C.P., Yiantsios, S.G., Karabelas, A.J., (2004). Numerical simulation of the flow in a plane-channel containing a periodic array cylindrical turbulence promoter, *Journal of Membrane Sciences*, 231, 81-90.
 - [32] DaCosta, A.R., Fane, A.G., Wiley, D.E., (1994). Net-type spacers: effect of configuration on fluid flow path and ultrafiltration flux, *Industrial & Engineering Chemistry Research*, 33, 1845-1851.
 - [33] Cao, Z., Wiley, D.E. and Fane, A.G., (2001). CFD simulations net-type turbulence promoters in a narrow channel, *Journal of Membrane Sciences*, 185, 157-176.
 - [34] Li, H., Bertram, C.D., Wiley, D.E., (1998). Mechanisms by which pulsatile flow affects cross flow microfiltration, *AIChE Journal*, 44, 1950-1961.
 - [35] Zydney, A.L., Colton, C.K., (1986). A concentration polarization model for the filtrate flux in cross-flow microfiltration of particulate suspensions, *Chemical Engineering Communications*, 47, 1-21.
 - [36] Ahmed, S., Seraji, M.T., Jahedi, J. and Hashib, M.A., (2012). Application of CFD for simulation of a baffled tubular membrane, *Chemical Engineering Research and Design*, 90, 600-608.
 - [37] Ahmad, A.L., Mariadas, A., (2004). Baffled microfiltration membrane and its fouling control for feed water of desalination, *Desalination*, 168, 223-230.