Development of Effective Water Cleaning Process Methods for F&B Water Filtration System

K Muthusamy, R Mahendran and E Natarajan
Faculty of Engineering, UCSI University, UCSI Heights, 56000 Kuala Lumpur. Malaysia

Abstract. The daily processes in an F&B (Food and Beverage) industry requires massive amount of water usage that is cleaned by a RO (Reverse Osmosis) membrane. The aim of this study was to study cleaning process of water filtration and propose a new membrane design module for a more efficient approach in cleaning. Membrane cleaning involving chemical and physical aspects has been discussed in this study. Physical cleaning requires the use of velocity and wall shear stress that have been focused on through simulation. In RO membrane treatment, particles are transported based on solution-diffusion mechanism and convective flow that have been studied for improvements in module design. A different structure of spiral-wound membrane module was constructed based on various winding angle and radius between one membrane leaves to another. The compatibility of the new membrane design has been tested through a commercial computational fluid dynamics (CFD) software simulation ANSYS Fluent v19.2. Fluids with varying Reynolds number in the range of 4000 to 6000 were integrated for testing. Both existing membrane model and new proposed membrane model were simulated with the same boundary conditions for a justifiable comparison. Based on this study, it was found that the new proposed triangular model was able to achieve higher velocity, wall shear stress and turbulent kinetic energy compared to the existing cylindrical model.

1. Introduction
The food and beverages industry are amongst the largest industry group in the world. They consist of many products such as fruits, drinks, dairy products, frozen food and many more. The daily operations of these industries involve massive amount of water usage [1]. The water that is being used is often supplied by the government from different sources such as lakes, rivers, sea and also groundwater. These water sources are unsafe for processing food and beverages if used directly without a method of treatment. Water and wastewater treatment play a significant effect on producing products that are safe to be consumed. Reverse Osmosis (RO) is an important segment of the water treatment. Membranes are used in a high-pressure vessel to remove impurities and supply clean water to the user. Generally, Spiral-Wound Modules (SWM) is the most commonly used membrane type and is in high demand. However, there are several aspects that are inevitable in membrane operations that are the susceptibility of a membrane to fouling as well as the requirement for regular cleaning of membrane.

In this review, we discuss the reason that causes fouling on a membrane as well as propose a new membrane structure that is capable reducing the formation of fouling on the membrane. The designing of new membrane structure was done with the aid of SolidWorks software. The design structure was based on a triangular prism as based on F. Springer et al. [2] that studied the wall shear stress and permeate flux for ceramic membranes found that triangular geometry was able to produce higher wall shear stress. Moreover, the modelling of flow through CFD was possible as many studies have been able to produce
similar results from CFD simulation when compared to experimental data. Y. Lie et al. [3] simulated the mass transfer in a slit membrane module which contained mixing-promoting baffles for an efficient removal of volatile organic compounds. R. Ghidossi et al. [4] conducted CFD simulation for different membrane models under laminar and turbulent conditions. In this study, triangular and cylindrical geometries were simulated under similar conditions. The cylindrical geometries were based on actual membrane model and the triangular membrane geometry was designed with appropriate dimensions to accommodate for cylindrical geometries. Turbulent flow throughout the membrane structures was simulated using CFD method in order to investigate the benefits of triangular geometry compared to the cylindrical. The turbulent flow was based on a range of Reynold’s number along with the inlet velocity. The outlet velocity, wall shear stress and turbulent kinetic energy were analysed.

2. Methodology

2.1 Model Geometry
The models of both housings and spirals were done for both triangular and cylindrical geometry. Cylindrical housing design dimension were referred to the product specification sheet of CSM RO membrane with inside diameter of 20.1 cm and length of 100 cm [5]. The triangular housing consists of an isosceles triangle with both sides at 20.225 cm and base of 25 cm along with a length of 100 cm. Both housing models were presented in figure 1. For the spirals, both circular and triangular have a similar spiral length to accommodate for fair comparison. The size of the pipe for fluid flow will be 0.5 mm and the space in between one pipe to another will be 0.8 mm [6]. Both triangular and circular spirals were shown in figure 2.

![Figure 1. Membrane housing: (a) Cylindrical, (b) Triangular.](image)

![Figure 2. Membrane spirals: (a) Circular, (b) Triangular](image)

2.2 Solution Method
The simulation of flow in all the geometries was done in ANSYS Fluent v19.2. A pressure-based solver was used to study the steady state condition of fluid flow. The viscous standard k-epsilon model with near wall treatment set to enhanced wall treatment to simulate the flow in the geometry to account for high Reynold’s number as the fluid flow is set to be turbulent. The fluid used in the flow was water with
density of 998.2 kg/m$^2$ and viscosity of 0.001003 kg/m.s. Water is considered to be a Newtonian fluid along with no-slip conditions applied to the walls of the geometry. Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) scheme was selected for solutions for all the simulation run. Green-Gauss Cell Based spatial discretization was selected as it is appropriate for non-uniform tetrahedral mesh. Pressure was discretized to second order. The momentum and turbulent kinetic energy were discretized to second order upwind to account for turbulent characteristics of the fluid as well as to obtain second order accuracy. The initialization of solution was done from inlet and the solution was set to converge once the global scaled residual values of the continuity equation falls below $1 \times 10^{-6}$ and the $x$, $y$ and $z$ velocity as well as the $k$ and epsilon fall below $1 \times 10^{-6}$. A total of 1000 iterations was set for each simulation run for better accuracy.

3. Results and Discussion

3.1 Velocity

The turbulent velocity profile of both housings is shown in figure 3. Both velocities show a turbulent profile, but the triangular housing achieves a higher flow rate before reaching the outlet. However, the cylindrical housing reaches the initial velocity of 4 m/s faster than the triangular housing and remains constant throughout. The triangular housing takes longer time to reach initial velocity of 4 m/s but reaches a higher overall flow rate before reaching the outlet. The increase in velocity can drastically reduce the formation of particle deposition on the membrane surface and as a result enhance the permeation flux rate of the membrane.

Figure 3, 4 and 5 shows the maximum velocities reached by both triangular and circular spiral at the outlet when assigned with inlet velocities of 4m/s, 5m/s and 6m/s respectively. It can be seen that the triangular spiral reaches a higher outlet velocity as compared to the circular spiral in all of the inlet velocity ranges. Based on figure 3, both spirals reach an outlet velocity range of 6 m/s but the triangular spiral reaches a maximum outlet velocity of 6.65 m/s whereas the circular spiral reaches a maximum outlet velocity of 6.29 m/s. The triangular spiral increased in velocity by 2.65 m/s whereas the circular spiral increased in velocity by 2.29 m/s when reaching the outlet. In figure 4, when the inlet velocity assigned was 5m/s, the triangular spiral reaches an outlet velocity of 8 m/s whereas the circular spiral reaches an outlet velocity of 7.7 m/s. The triangular spiral increased by 3 m/s and the circular spiral increased 2.7 m/s when reaching the outlet. In figure 5, both spirals reach an outlet velocity range of 9 m/s but the triangular spiral reaches a maximum velocity of 9.5 m/s whereas the circular spiral was only able to reach a velocity of 9 m/s. The triangular spiral increased by 3.5 m/s and the circular spiral increased 3 m/s when reaching the outlet. Figure 6 shows the outlet velocity of spirals when inlet velocity was 6 m/s. Both spirals reach an outlet velocity range of 9 m/s but the triangular spiral reaches a maximum velocity of 9.5 m/s whereas the circular spiral was only able to reach a velocity of 9 m/s. The triangular spiral increased by 3.5 m/s and the circular spiral increased 3 m/s when reaching the outlet.

There is a steady increase in outlet velocity for both spirals as the inlet velocity increases. The range at which the velocity increases also varies depending on the inlet velocity assigned. The higher the inlet velocity the higher the increase in outlet velocity range. However, the triangular spiral in all cases reaches a higher velocity than the circular spiral. This can aid in enhancing the permeate collection rate by reaching the center collection pipe faster.
Figure 3. Turbulent velocity profile for both housings

Figure 4. Maximum outlet velocity reached by both spirals when inlet velocity is 4 m/s

Figure 5. Maximum outlet velocity reached by both spirals when inlet velocity is 5 m/s

Figure 6. Maximum outlet velocity reached by both spirals when inlet velocity is 6 m/s

3.2 Wall shear stress

The wall shear stress of the cylindrical housing and triangular housing were shown in figure 7 and figure 8 respectively. Based on figure 7, the wall shear stress at the inlet of the cylindrical housing is much higher than the outlet. This can cause particle deposition at the outlet of the membrane housing to be higher than the inlet as lower wall shear stress regions are more susceptible to particle deposition. From figure 8, the triangular housing shows high wall shear stress at the edges of the inlet. Moreover, the overall wall shear stress throughout the triangular housing is uniform. It is also noticeable that the overall wall shear stress of the triangular housing is higher than the cylindrical housing. This indicates that the triangular housing is less vulnerable to fouling as compared to the cylindrical housing.

The 3D illustration shows the location at which maximum shear stress occurs for both spirals. The wall shear stress for circular spiral is shown in figure 9. It is noticeable that the wall shear stress throughout the spiral is constant except at the outlet. The wall shear stress increase at the outlet of the circular spiral is similar to that of triangular spiral and is due to increase in velocity at the outlet. The wall shear stress for triangular spiral is shown in figure 10. It can be seen that the movement along the triangular spiral have a constant wall shear stress except for the corners. There is a notable increase in wall shear stress at the corners of the spiral. The location of high wall shear stress can prevent the deposition of unwanted particles on the membrane surface. This does not only reduce the fouling on membrane surface but also aids in the regeneration cleaning process [2]. The triangular spiral is capable of being more efficient in
membrane process as compared to the circular spiral because of its high wall shear stress fluctuations that can improve filtration flux.

![Figure 7. Wall shear stress for cylindrical housing](image)

![Figure 9. Wall shear stress for circular spiral.](image)

![Figure 8. Wall shear stress for triangular housing](image)

![Figure 10. Wall shear stress for triangular spiral.](image)

3.3 Turbulent Kinetic Energy

Figure 11 shows the turbulent kinetic energy profile for triangular and cylindrical housings. It can be observed based on figure 11 that there are fluctuations in the turbulent kinetic energy for both housing. It can also be noticed that the outlet of the triangular housing reaches 1 m²s⁻² at the outlet whereas the cylindrical housing reaches 0.8 m²s⁻² similar to its inlet. Therefore, the turbulent kinetic energy is higher for triangular housing as compared to cylindrical housing. This shows that the flow in triangular housing is more turbulent than that of cylindrical housing. The turbulent kinetic energy influences the particle deposition on the boundary layer of the membrane. Turbulent flow and disruption of concentration at boundary layer are directly proportional [7]. The higher turbulent flow characteristic of the triangular housing has better potential in minimizing the particle deposition on the membrane surface compared to the cylindrical housing. This can have a significant reduce the formation of cake layer on membrane surfaces.

Figures 12, 13, and 14, show the turbulent kinetic energy for triangular and circular spirals when inlet velocities are 4m/s, 5m/s and 6m/s respectively. Based on figures 12, 13, and 14, the turbulent kinetic energy for triangular spiral is higher than the circular spiral in all cases. Initially, the circular spiral starts off higher than the triangular spiral but eventually the triangular spiral reaches a much higher turbulent kinetic energy in all ranges of velocity. It can be seen as the velocity increases; the turbulent kinetic energy increases as well. The peak differences between both spirals increases in range as the velocities increase. In figure 12, it can be noticed that the circular spiral has a more significant drop in turbulent kinetic energy as compared to the triangular spiral. Based on figure 13, the circular spiral still has a significant decrease in turbulent kinetic energy whereas the triangular spiral’s drop greatly reduces as
compared to figure 12 as well as increases slightly towards the end. Moreover, figure 14 shows that the turbulent kinetic energy for circular spiral still decreases consistently. For the triangular spiral, the turbulent kinetic energy drop reduces further as compared to figure 13 and it significantly increases above the initial peak after the drop as shown in figure 14. As the inlet velocity increases, the drop in turbulent kinetic energy for triangular spiral decreases whereas the circular spiral drops consistently in all cases. This indicates that the triangular spiral has a higher capability to maintain turbulent flow as compared to circular spiral. The fluid motions kept turbulent can greatly disturb the concentration of boundary layer, hence reduce the formation of cake layer on the membrane surface [3].

4. Conclusion
In this study, the turbulent flow in membrane housings and membrane spirals were simulated using CFD to better understand their hydrodynamic behavior. The outlet velocities, wall shear stress and turbulent kinetic energy were analyzed based on a range of inlet velocities. For the housings of membrane, it was noticed that the triangular housing reaches a higher outlet velocity compared to the cylindrical housings. This can aid in transportation of fluid from one membrane to another within a membrane system. Moreover, the wall shear stress is more evenly distributed in the triangular housing that makes it less susceptible to fouling deposition on membrane surface. The turbulent kinetic energy in triangular housing helps maintain a turbulent flow throughout the fluid transportation. From the results obtained, it can be stated that the triangular housing is capable of better overall membrane operation compared to the cylindrical housing. For the spirals, as the inlet velocities increase there is an increase in outlet velocity for both spirals. However, the outlet velocities for triangular spiral reaches a higher peak in all cases when
compared to the circular spiral. This can aid in the permeate transportation to the center pipe of the membrane. Furthermore, the wall shear stress for the triangular spiral was substantially higher at the edges. The high wall shear characteristic of the triangular spiral can improve the filtration flux of the membrane resulting in a more efficient membrane operation. For the turbulent kinetic energy, the triangular spiral maintains a higher value but the drop upon reaching a peak value varies in all cases. It can be observed that as the velocity increases the drop in turbulent kinetic energy decreases for triangular spiral whereas the circular spiral still drops consistently. This indicates that the triangular spiral is capable of maintaining a better turbulent flow compared to the circular spiral resulting in better diffusion flux of the membrane. It can be stated that the objectives of this project were achieved as the new proposed design consisting of triangular geometry was able to stay ahead of the existing cylindrical model in all aspects. This can significantly enhance the overall membrane operations by improving efficiency and reducing the need for frequent membrane cleaning.

5. References

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