Improving the Efficiency and Stability of Centrifugal Pump Filtration System Using Membrane System

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Abstract
Centrifugal pump performance is reported to be low when the pump is exposed to contaminated fluids during operation. The contaminated fluids are reported to have caused pump scaling and fouling. Most centrifugal pumps are reported to have been damaged due to pump scaling and fouling. The suction strainers are usually used to prevent scaling and fouling by preventing unwanted impurities from getting into the centrifugal pump system during operation. The current suction strainers used in a centrifugal pump system have pore sizes that are poorly characterised leading to the current problem of poor separability during pump operation. Membrane technologies used in separation technology are reported to have better separability if the membrane pore sizes are properly characterised for optimal separability. In the current study, a new approach is used to design suction strainers using membrane technology for efficient and stable performance of the centrifugal pump. The tools of computational fluid dynamic and stochastic mechanics are used to model the fluid flow characteristics, and to characterize the membrane pore size distribution without the flow of impurity in the pump system for efficient, and stable performance. The following facts are theoretically derived and validated after theoretical modeling and simulation of the relevant parameters. The first signal of fouling of a membrane is a reduced volumetric flux, and this is caused by resistance which is due to concentration polarisation and reduced mass transfer coefficient. It was also shown that the design membrane has its own resistance which, when kept to a minimum will have a high initial volumetric flux. A better performing membrane will have a low resistance which subsequently will increase the initial volumetric flux, consequently increasing the rate at which fouling occurs. It was also shown that the trans-membrane pressure is directly proportional to volumetric flux; however there is a deviation when impurities are deposited onto the membrane surface and into the membrane pores.

Keywords
Centrifugal pump, Fouling, Performance and Stability.

1. Introduction

A centrifugal pump can get blocked during pump operation due to many factors such as sand, sanitary towels (Sewerage industries), high viscosity oils and grit (Mckee al. 2011). These blockages cause the pump performance and efficiency to drop during operation. The suction/discharge pressure drops leading to pump cavitation that destroys the impeller vane (Sreedhar et al. 2017). This reduces the efficiency and performance of the pump (Yang et al. 2018). The next time the pump is run, it takes a longer period before enough suction pressure is accumulated by the device. Eventually, when enough suction pressure has been accumulated, the pump performance and efficiency is observed to be very low. Investigation revealed that this was caused by blockages in the pump system, particularly the suction line (Aissa 2009). It further causes a number of problems such as more downtime for maintenance, shortens the lifespan of these pumps and causes more money to be spent.

Over the years, many researchers have tried different methods to address this problem of fouling and blockage in a centrifugal pump that causes cavitation (Tulleken 2012). One researcher observed impurities through screens to increase pump performance in the Western Cape Province (Tulleken 2012). The employment of suction strainers to protect the pump for filtration purposes is not efficient because of the habit of the strainer to experience fouling after a certain period of time of operation; this lowers the strainer performance leading to a low pressure at the pump which continues to fuel the current problem (Kumar et al. 2018). In terms of membrane technology, there are advances for the current pump problem, however, it is noted that the biggest disadvantage of membrane technology is fouling (Amira 2019). The pores of the membrane are blocked by impurities during filtration process, as a result, the blocked membrane pores reduces in radius and this restricts the filtration process (Jelemensky et al. 2014). This hinders the progression of membrane technology.

Membrane fouling is caused by sieving and adsorption of particles and compounds onto the membrane surface or within the pores (Abdelrasoul et al. 2013). The most frequently used method to reverse fouling is a method called membrane backwashing. However, its limitation is it removes only a fraction of a fouling (back-washable) but fails to handle the non-back-washable one (Kisielus 2012). The current problem faced is that filters have poor pore size network, consequently the dirt or impurities are allowed to pass through the filter and become detrimental to the centrifugal pump. However, the problem seems to persist because pumps are designed for water as a working fluid (Tulleken 2012). Whenever a pump encounters fluids of different viscosity and properties the performance is affected, higher viscosity fluids also tend to reduce the pump efficiency and performance. This also happens when water as a working fluid contains foreign solid objects such as impurities. This problem has not been well investigated since the current problem is persisting. This is why it is very imperative to model a system that will prevent impurities from getting into the pump with high performance.

2. Literature Review

The preceding chapter of this project provided a general literature review of centrifugal pump blockages and fouling. This chapter serves to broaden the understanding of the current problem faced by pump engineers. The chapter deals with centrifugal pump anti-fouling technologies and their challenges such as membrane fouling, strainer fouling and strainer degradation during pump operation. Previous work done to alleviate the above mentioned problems are faced by several limitations leading to the current problem faced by pump engineers. These problems are discussed in this chapter. Their successes and achievement are also highlighted in this part of the project. The rational and model selection is also highlighted in this part of the project.

Tulleken (2012) found that sewage contains solids which cause reduction in pump performance due to blockages. In order to avoid scaling, fouling and blockages in the pump station, Screens are employed as a filter. The screens also suffer blockages due to cake layer build up and need to be cleaned on a regular basis depending on their usages. According to research, it is recommended that all pump stations should have at least one stand-by pump (Jones 2006) and CSIR 2003). However, due to fouling both pumps will still face the same problem. Suction strainers are also used to prevent impurities from entering the pump (Pushpdant and Prabhash 2012). The suction strainers are efficient. However, their limitation is that strainers often get blocked when the impurities get accumulated on the surface of the strainers. This causes the pump to soon start going through cavitation, starvation and possible premature failure (Pushpdant and Prabhash 2012). However, it is much better to use a strainer instead of a filter, because a filter has more chances of clogging. An investigation was done where a pump used soft slurry as a working fluid (Mohamed et al. 2013). The results showed that the pump head and efficiency were lower while there is an increase in the shaft power as compared to clear water as a working fluid. Another conclusion drawn from the experiment is that the reduction factor of efficiency is a little bit lesser than the reduction factor of the head. This proves why the performance drops whenever slurry is being pumped using a centrifugal pump. The suction strainers improve performance to some extent. Kumar et al. (2018) undertook an investigation to modify the design of Y-shaped strainers to decrease the head loss for optimal operation. They tested the original design of the strainer under various operational conditions, and observed the results. They further investigated reasons that account for the increases in the head loss and used these reasons to modify the design for improved performance. Smarajit (2016) presented the creative uses of membrane technology and its efficiency in separation of gases, solids and liquids. "One of the most imperative advantages of the membrane technology is a long membrane life operating for over 10 years", says Roy. Membrane Technology is easy to use, reliable and very flexible. In the maritime industries, for hydroelectric power generation, the fresh and salt water are separated by a membrane. This is made possible by the fact that only the molecules of water can pass through the semipermeable membrane. This allows for the separation. And due to the pressure difference, a turbine is run to generate electrical energy. Amira (2019) presented on the advances in membrane technology and their importance in delivering sustainable water to the entire globe. The study further touches on the efficiency of the membrane technology in producing solutions to environmental problems. However, it is further noted that the existing disadvantages of membrane technology is fouling. So, the research studies involve membrane designs with antifouling. Jelemensky et al. (2014) reported time-optimal control of a membrane diafiltration process where there was the presence of membrane fouling. The pores of the membrane were blocked by impurities. And, the blocked membrane pores reduces in radius and this restricts the filtration process. It causes a very low efficiency in the filtration process. For their study, they used a principle called 'Pontryagin' to solve the problem. This method enabled them to solve the problem in a fashionable manner. It is commonly utilised in solving problems of models of diafiltration processes. Kisielus (2012) reported a study on membrane fouling. He further investigated the role of Transparent Exopolymer Particles (PET). This research study was reduced to examine one feed water constituent because it was suspected to increase fouling in the early stages more than any other factor. Membrane Technology employs a variety of uses but the main setback, like all the other studies, includes fouling and scaling. The most frequently used method to reverse fouling is a method called membrane backwashing (kisielus 2012). The most important parameter of the membrane is the pore size which is characterised by the application range and operational pressure. Generally, the opening size of the filtration screen is expected to be approximately one half of the largest allowable particle (Shinde and Wankhede 2018). The largest allowable particle is described as the size of particle that can pass through the downstream equipment without damaging the equipment. Furthermore, the amount of debris in the flowing media should also be considered when selecting the suitable opening size.

3. Methods

3.1 Model Identification and Modification

In identifying the relevant model, the choice of relevant parameters is important and thus plays a big role in solving the problem at hand. The model identified was then modified according to CFD principles and each parameter investigated to see its impact on alleviating or promoting the problem. A flow in motion can either be laminar or turbulent and that is given by the Reynold's number below (Dixon and Hall 2014).

$$R_e = \frac{Inertia\ force}{Viscous\ force} = \frac{\rho U_m D}{\mu} \quad (1)$$

Where ρ=density, U_m=mean velocity of flow, D= diameter of pipe and μ= dynamic viscosity of the fluid. The equation models the ratio of the inertia force to the viscous force in the fluid. When the value of Reynold's number is greater than 4000, the flow is said to be turbulent, which means that the layers of flow are mixing. And, when the Reynold's number is less than 2300, the flow is said to be laminar, which means that the flow layers are taking a straight path and (Reynolds 1883) and (Dixon and Hall 2014). The flow rate is inversely proportional to the resistance in a flow as given by (Dunn 2010)

$$Q = \frac{\Delta P}{R} \quad (2)$$

Where, Q=flow rate, R=flow resistance and ΔP=pressure drop.

This means that in order to have more flow rate, the flow resistance would need to be decreased. This equation is analogous to that in electrical called 'ohms law'.

3.2 Filtration models

Porosity is a measure of the ratio of the holes to the solid part of a material. Basically, it tells how much of the material can allow flow to pass through and is given by an equation by (Munir 2006).

$$\mathcal{E} = \frac{A'}{A} \quad (3)$$

Where Ɛ=membrane porosity, A′=Actuall cross sectional area of the flow and A= Full cross sectional area.
Having modelled the porosity of the material, a change in pressure can now be modeled as follows. This is called the Carman-Kozeny equation for flow through a porous media (Dunn 2010)

$$\frac{dp}{dx} = \frac{\Delta P}{L} = -\frac{180\mu u(1-\mathcal{E})^2}{{d_s}^2\mathcal{E}^3} \quad (4)$$

Where L=length of the filter, $\boldsymbol{d_s}$=Diameter of the solid particles, $\boldsymbol{\mu}$=Dynamic viscosity and $\boldsymbol{u}$=mean velocity

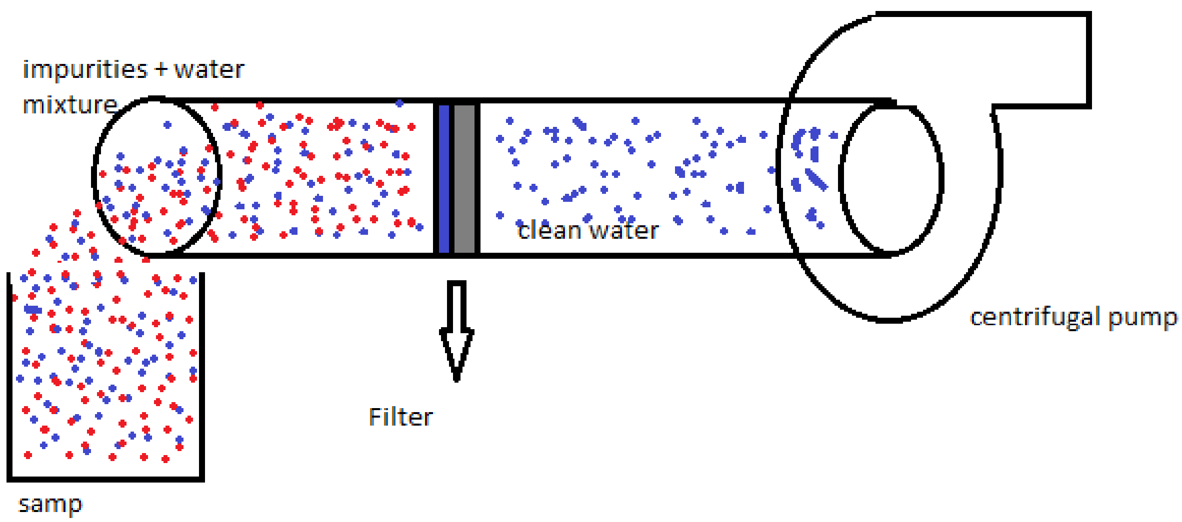

Figure 1: Showing fluid system with membrane filtration

3.3 Dead End Filtration

A dead end filtration is the one where the flow of water is perpendicular to the surface of the membrane surface. The water is pushed through by the pressure difference caused by a pump, for example. However, the impurities build up on the membrane surface and this causes the resistance of the membrane to increases, hence deceases the permeate flux (Munir 2006).
The hagen-Poiseuille equation models the flow of water and assumes the pores are parallel and cylindrical.

$$\boldsymbol{J} = \left(\frac{\mathcal{E}_m r^2}{8\mu\tau}\right)(\boldsymbol{\Delta P}/\mathrm{X}) \quad (5)$$

Where J= the flow flus, $\boldsymbol{\Delta P}$=the pressure difference, X= the membrane thickness. Also, the Flux can be related to the total hydraulic resistance by the Darcy's law given by (Munir 2006).

$$\boldsymbol{J = \frac{\Delta P}{\mu(R_m + R_c)}} \tag{6}$$

Where R_m =the membrane resistance and R_c=cake resistance

Also, assuming the pores to be perfect cylinders, the permeability of the solvent can be determined using the Hagen-Poiseuille equation. This shows the volume flow rate of the solvent through the membrane (Siddiqui et al. 2016).

$$\boldsymbol{Q = \frac{\Delta P}{8\mu X} N_p \pi r^4} \tag{7}$$

Where Q=volume flow rate and N_p=number of pores in the membrane.

$$\boldsymbol{J_v = \frac{Q}{A_{mem}}} \tag{8}$$

There is also a relationship between the volumetric flux and the membrane area as shown below (Siddiqui et al. 2016).

A_{mem} = membrane area which is defined by:

$$\boldsymbol{A_{mem} = \frac{N_p \pi r^2}{\varphi}} \tag{9}$$

3.4 Model Modification

In order to avoid membrane fouling, the membrane flux should be kept constant. The modification is made on the assumption of constant flux for no fouling process.

From equation 2, the change in pressure becomes: $\boldsymbol{\Delta P = QR}$ (10)

Assuming no cake formation ($\boldsymbol{R_c = 0}$) and substituting equation 10 into equation 6 yields:

$$\boldsymbol{J = \frac{QR}{\mu R_m}} \tag{11}$$

$$\boldsymbol{QR = J\mu R_m} \tag{12}$$

Substituting equation 12 into equation 7 models the thickness of the membrane for no membrane fouling case.

$$Q = \frac{J\mu R_m N_p \pi r^4}{8\mu X}$$

Making the membrane thickness the subject of the formula yields:

$$\boldsymbol{X = \frac{J\mu R_m N_p \pi r^4}{8Q\mu}} \tag{13}$$

Also from the continuity equation $Q = AV$

Substituting the continuity equation into equation 2 yields:

$$\boldsymbol{\Delta P = A_{pipe} V_{average} R} \tag{14}$$

Assuming that the membrane and the pipe have the same diameter since the membrane will be fitted into the pipe, $A_{pipe} = A_{membrane}$

From equation 14, the pipe area can be made the subject of the formula and substituted into equation 9 where it is equals to the area membrane.

$$A_{pipe} = \frac{\Delta P}{V_{avg} R} = A_{membrane} = \frac{N_p \pi r^2}{\varphi}$$

$$\Delta P = \frac{V_{avg} R N_p \pi r^2}{\varphi}$$

Also from equation 6, $\Delta P = J R_m \mu$

$$\therefore J = \frac{V_{avg} N_p \pi r^2}{\mu\varphi(\frac{R_m}{R})} \qquad (15)$$

Equation 15 models the membrane Flux in terms of the ratio of the membrane resistance to flow resistance for no cake formation condition.
Deriving the flux equation for the cake formation condition yields equation 16.
Only in equation 16 there is cake resistance term (fouling).

$$\therefore J = \frac{V_{avg} N_p \pi r^2}{\mu\varphi(\frac{R_m}{R}+\frac{R_c}{R})} \qquad (16)$$

4. Results and Discussion

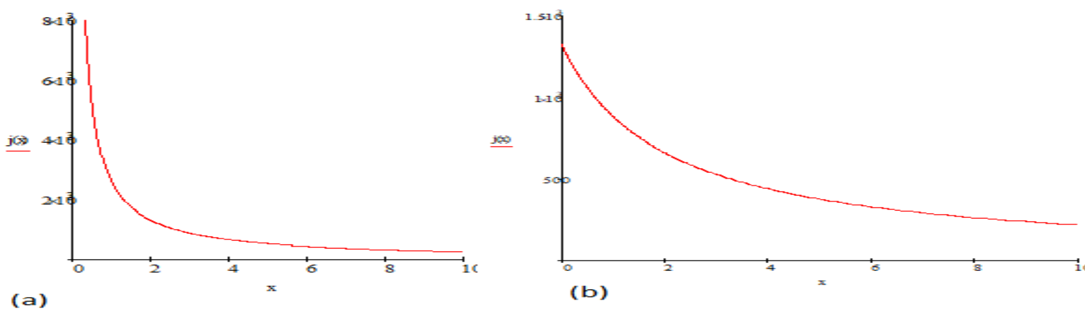

Figure 2: Flux vs resistance ratio

It is observed as shown in figure 2(a) that decreasing membrane resistance results to an increase in membrane volumetric flux during pump operation. It is shown that at a very low membrane resistance the volumetric flux increased to a very high rate, therefore to increase volumetric flux during pump operation the membrane resistance must be very low as shown in this study. The increase in flow flux at very low resistance is due to the following reasons. Firstly, Resistance opposes flow, so when there is less of it, permeate is able to flow through the membrane. This means there are lesser forces opposing the volume of flow that comes from the membrane. However, as shown in the figure, when the resistance becomes more, the permeate flux decreases because the high resistance decreases the driving force for the flow to be transported across the membrane surface. Membrane drag forces and high surface roughness increase the resistance of the moving fluid. At a lower resistance there is more permeating coming out of the membrane per unit time. This is because the membrane does not oppose flow as much as it would when there was more resistance. Also, an increase in flow rate improves mass transfer coefficient and reduces concentration polarisation and accumulation of retained solutes on the membrane surface (Vladisavljevic et al. 2003). Furthermore, higher temperature increased permeate flux caused by the lower permeate flux. The similar results were also found by (Vladisavljevic et al. 2003).

Figure 2(b) validated the observation shown in (a) which states that more resistance decreases volumetric flux. And, the lesser the resistance, the more the volumetric flux. In Figure 2(b), however, the rate at which membrane flux drops is more rapid as compared to the first figure. This is because, during fouling, there is more resistance build up due to the cake layers on the membrane surface. This cake layers are formed by particles deposited on the membrane surface which oppose the transmission of flow through the membrane. In other words, the only resistance present at this particular case is not just the membrane resistance but also cake layer resistance. This reduces the mass transfer coefficient and increases concentration polarisation, which consequently promote fouling even in the pore internal surface area. This increased concentration causes the decline in the volumetric flux. The gel layer model causes a decline by adding resistance to the membrane resistance (Nakao et al. 1986).

In a nutshell, the design of a better filter will be the one where the total resistance is kept to a minimum. This will give a bigger flux and hence better performance. Also, a minimum resistance will give the membrane a much longer time before the fouling can occur. Therefore a clear correlation is observed in the current studies and fluid mechanics impacts on fluid friction during system operation.

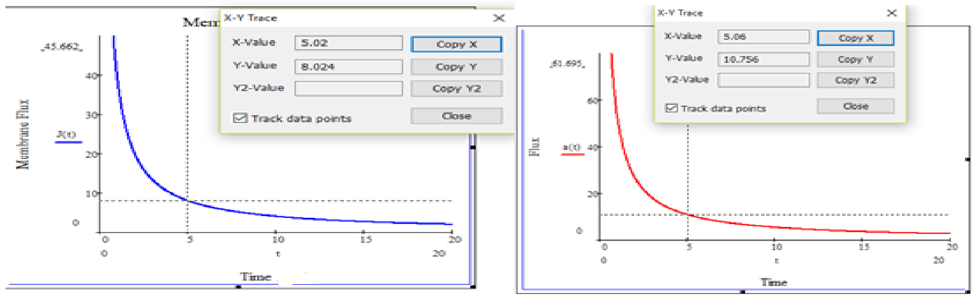

Figure 3: Shows Flux value at t=5

It is observed in Figure 3 that the thinner the membrane, the more the volumetric flux will be. And when the volumetric flux is higher, it takes much longer for it to drop. The figure above shows two different models, one thick and one thin. And as observed, after t=5min of operation, the thinner membrane has a higher volumetric flux as compared to the thicker one. This is because the membrane material has a certain resistance, and the more material used, the more the resistance which consequently reduce the volumetric flux. Similar results were found in other studies such as (Kim and Lee 2015) and (Mousavi et al. 2010).

Figure 4 below shows the results of the flow rate along the number of iteration made at each section of the water tunnel.

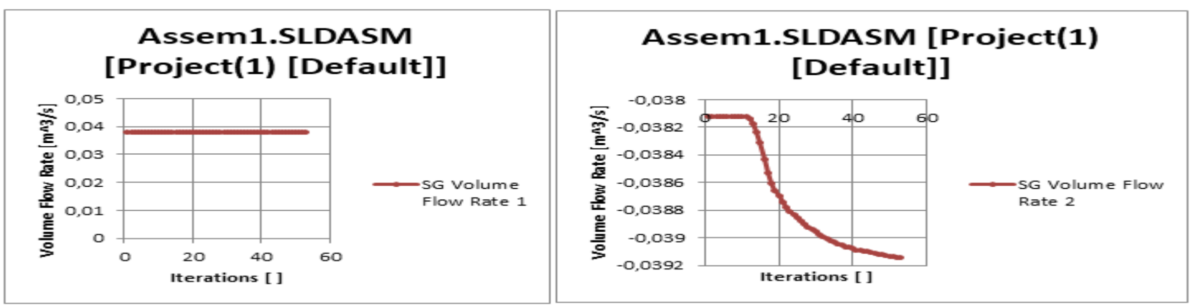

Figure 4: Volume flow rate both at inlet and exit of the tunnel

The results in Figure 4 showed that the flow rate was constant just before entry to the membrane. This followed the continuity laws because of constant tunnel cross sectional area (Dixon and Hall 2014). However, it dropped inside the membrane and this was caused by the porous medium resistance (Mahendran et al. 2004). As soon as the first cake layer is formed, the flow rate decreases. Assuming that the flow rate is constant will results in the pressure drop increasing linearly, proportional to the amount of solid deposited on the membrane surface. The negative sign shown on the graph simply shows the direction of view with respect to the entry or inlet of the water tunnel, 1 and 2 denotes inlet and exit of the water tunnel respectively.

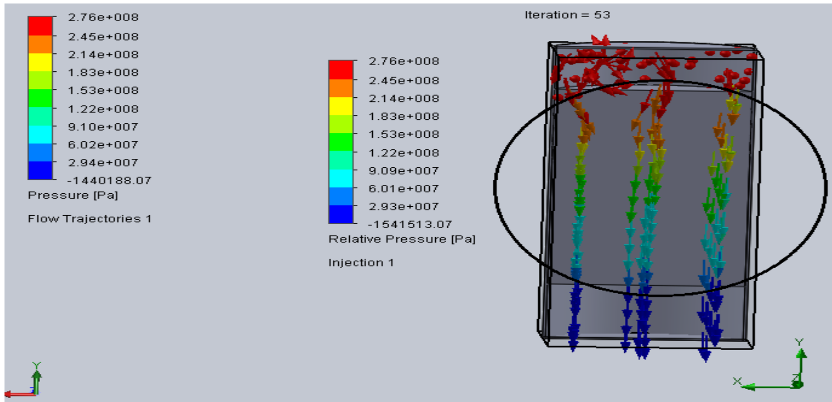

Figure 5: Showing flow trajectory and Pressure variation

As observed, figure 5 shows the pressure distribution for a membrane with a high resistance and placed just next to the tunnel entry. As seen, in the figure 5above, the pressure is higher at tunnel entry as previously explained. Furthermore, the TMP is an indication of the fouling taking place with respect to time. This is due to the combination of sieving, adsorption of particulates and compound onto membrane surface or within the pores (Abdelrasoul et al. 2013). However Munir (1998) reported that the flow rate or turbulence, whether due to pumping or moving the membrane, has noticeable effect on the permeate flux. This is also the same as show in the figure above. Furthermore, the advantage of having such membrane is that, when there is fluid mixing as shown above, the mixing fluid can sweep away the accumulated solute, therefore reducing the hydraulic resistance of the cake and reducing the thickness of the cake (Qusay et al. 2013).

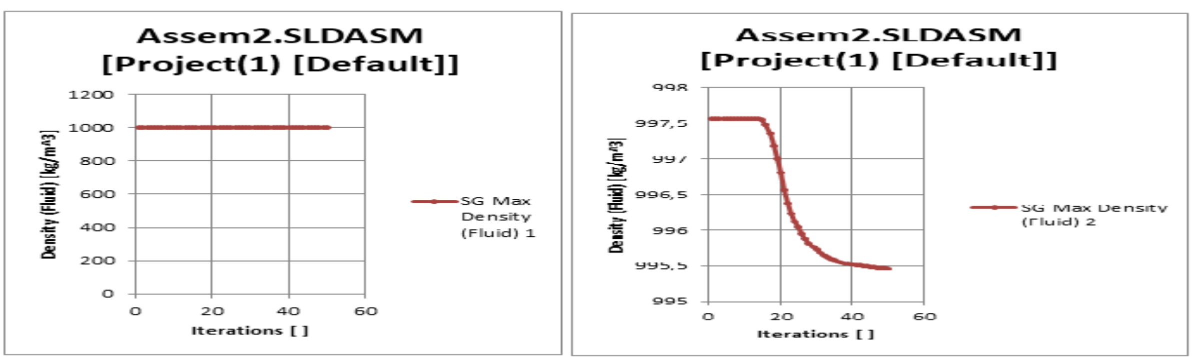

Figure 6: Density variation across the flow (thick)

According to a paper by Said et al. (2013), a direct proportional relationship exists between density and concentration. This means that when density increases, the concentration will also increase and vice versa. With that being said, it is easier to understand that a membrane filter that has filtered properly should produce a permeate with lesser concentration or density. Now, looking at Figure 6, it is observed that prior to the membrane, the density/concentration is constant. This means that the concentration of the impurities and water has not changed. However, out of the membrane it is observed to have changed. This is because the impurities have been filtered and are on the membrane surface. However, it is worth noting that, for a membrane with a bigger thickness, the concentration does not drop that much because of the high resistance which opposes the permeate flow (Vladisavljevic et al. 2003).

5. Conclusion

A number of conclusions were drawn based on the results found in this project. From the results of the membrane resistance, it can be concluded that a membrane has its own resistance based on its material. This resistance is responsible for reducing volumetric flux during operation. However, as also shown, the membrane resistance depends on the thickness of the membrane. Therefore, to reduce the resistance, the membrane has to be very thin. With respect to time, the thin and thick membrane were compared for 5 minutes and results showed how the flow rate had dropped in each one. For a thin membrane, the flow rate was still higher than the thick membrane and this is due to the amount of resistance that is present when a membrane is thick. That is why a thick membrane is quick to have cake layer formation.

From the concentration results, it can be concluded that the concentration of the fluid before and after the membrane should not be the same. When a membrane is effective, the concentration of the fluid after the filtration should be lower. And, as concluded from the results, this is better achievable with a membrane of lower resistance.

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