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Comparison of Different Pitch Lengths on Static Promoters for Flux Enhancement in Tubular Ceramic Membrane

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Abstract: The use of turbulence promoters in membrane based processes have been investigated and are increasingly been used in industrial applications to minimize fouling and enhance the membrane flux. The efficiency of crossflow microfiltration is limited by membrane fouling and concentration polarization leading to flux decline during operation. A detailed study was carried out in the microfiltration of yeast suspensions using an in-house rig and three different static turbulence promoters of varying pitch lengths. The design of the promoters incorporates a helical thread around the length of the insert, which induces turbulent flow through the membrane. This promotes good mixing of the feed fluid and minimizes concentration polarization effects. The testing of tubular membranes with the static inserts has been carried out and the results are included in the report. The pitch lengths used were 7 mm, 10 mm, and 14 mm and the parameters investigated included temperature, CFV, concentration of feed suspension and pressure. The flux decline data was recorded over a 50 minute filtration cycle and the cleaning protocol was employed after every cycle to restore the permeability of the membrane. A comparison of the membrane performance and efficiency of the three swirls inserts of varying pitch lengths together with a comparison of the degree of total, reversible, and irreversible fouling data amongst others are reported and discussed. The results obtained during the investigations of flux enhancement via static turbulence promoters into the tubular membranes are presented and are selected to differentiate the efficiency of the inserts and the degree of fouling associated with them.

Keywords: Turbulence promoters, ceramic, yeast, pitch length, tubular, fouling

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INTRODUCTION

Ceramic membranes have been used and are currently one of the areas of research geared towards applications in food, chemical, biochemical, energy, environmental, and water treatment engineering. Research on this type of membrane and utilization of ceramic membranes have increased significantly over the last ten years due to their outstanding heat resistance, solvent endurance, and resistance to acid and alkali. Enhancement of the performance and efficiency of the membrane separation process is a very popular topic in the research fields of membrane separation because of the problems of concentration polarization and subsequently, membrane fouling. These effectively cause a reduction in the performance of the membrane and usually causes permeate flux to be too low to adapt to technological and economic requirements.

Turbulence promoters are used to create unsteady fluid instabilities, which induce turbulence via feed spacers and static mixers. These fluid instabilities have been used to disturb foulants, while channels with irregularities have been utilized in inducing mixing at the membrane/solution interface (1–4). A different method that has been used to enhance the performance of the filtration process is to promote turbulence using baffles and stamped membranes. Elmaleh and Ghaffof (5–6) used a UF membrane with helical baffles introduced in the filtration element. Significant flux improvements were reported. (7) used a helical stamp on the inside of a tubular ceramic MF membrane. The results from this showed that compared with a smooth-surface membrane, the permeate flux increased by a factor. Among all the hydrodynamic methods used for improving mass transfer in crossflow membrane filtration, an increase in cross-flow velocity surely represents the simplest way to create turbulence and reduce membrane fouling. The resulting turbulent shear stresses thin and mix the fluid in the boundary layer with the bulk flow. Its application is limited however by high processing costs and large variation of pressure along the membrane length. The use of static turbulence promoters represents the next simplest method for increasing shear rate in the vicinity of the membrane surface.

Other techniques used to disrupt the boundary layer and enhance cross-stream mixing include inserts in the flow channel (8) and variations in the geometry of the filtering surface (9). Intermittent jets and pulsatile flows have also been shown to be effective (10, 11) and a rotating blade has been used to increase shear rates in a flat plate module (12). Taylor vortices (13), Dean Vortices (14, 15), and pulsatile flows in passages, which are specially designed to generate vortices, have all been shown to reduce concentration polarization and increase filtration fluxes (16, 17). The present research carried out to investigate the effect of pitch length on flux enhancement aims to highlight the importance of promoter geometry on membrane flux within a given membrane length. Previous research has focused on the improvement of flux with an insert but the degree of improvement can be further investigated by altering the insert. Here, the effect of the pitch length is the focus of the research and its effect on membrane flux.

High fluxes can be achieved with much lower crossflow rates than are required for turbulent flow. However, channel pressure drops are quite high in helical passages, even with low flow rates, since sufficient energy must be supplied to keep the fluid rotating. Therefore, short module lengths are very ideal when helical inserts are used within a tubular membrane module. Copas and Middleman (18) investigated the ultrafiltration of a latex suspension in a tube with kenics static mixer as a turbulence promoter under turbulent flow conditions. There was a significant improvement in the permeate flux and this was attributed to a reduction of the gel layer resistance at the membrane surface. The maximum of flux enhancement was explained by fluid flowing in the presence of the static mixer. At very low Reynolds numbers the swirling flow generated by the mixer is insufficient to alter convection at the membrane surface to a significant degree. At very high Reynolds numbers, the level of turbulence in the empty tube is so high that the addition of a swirling component of flow does not bring about a major improvement in the permeate flux.

Fluid flow over static turbulence promoters give us an idea as to the mechanism involved in the flow through tubular membranes. The promoters reduce membrane fouling by producing a helical flow pattern and generating a secondary flow to fight the formation of a concentrated gel layer immediately above the membrane surface. The helical flow is the pattern of flow over the helical grooves of the promoter. These create fluid instabilities in the feed and consequently mechanically scour the membrane surface. The helical inserts used in this particular study are expected to be more efficient than rod inserts due to a better mixing by the vortices between the boundary layer of the membrane and the feed fluid. This further minimizes concentration polarization effects and fouling. Gupta et al., 1995 (8) also reported that three flow structures coexist around helically shaped inserts located in a tubular membrane: Tangential flow component in the space between the helices and the membrane surface and it represents a smaller fraction of the total flow; Rotational flow following the shape of helices and it represents the main part of the flow; Reverse flow component generated by secondary flow near the surface of the rod on the downstream side of the spiral. With the reduction of the insert diameter, a tangential flow component in the neighborhood of the membrane surface becomes a more significant fraction of the total flow, thus reducing the degree of turbulence on the membrane surface and insert efficiency.

Problems with membrane stability occurring in configurations with polymeric membranes were significantly reduced or even completely eliminated by using ceramic membranes. Different shapes of static turbulence promoters such as spiral wire, static rods with and without baffles, metal grills, disc and doughnut shape inserts have also been investigated (19, 20). Significant improvements in flux were realized but the pressure loss induced by the promoters increased the power for fluid circulation, thus leading to increased energy consumption. Additionally, the pressure drop increase via static turbulence promoters can cause a high TMP variation across the length of the membrane. This is a disadvantage as operation at low TMP was found as essential in the prevention of extensive fouling of the membrane (21). The results of parallel studies along with further development of ceramic membranes induced investigations on incorporating static turbulence promoters, especially helical-shaped ones (22).

The intent of this work carried out is to characterize accurately, through experimental investigations and approach, the hydrodynamic behavior of three turbulence promoters of varying pitch lengths and their effects on membrane flux. The results are expected to show trends justifying better performance with different promoters under different experimental conditions. Microfiltration experiments were carried out under different experimental conditions of temperature, pressure, feed concentration, and crossflow rates. Previous research has investigated the effect of different helical baffle geometries in microfiltration but this paper focuses on the pitch length as a determinant in the flux enhancement process. The aim of this paper is to correlate the performance of new tubular ceramic membranes with the three different turbulence promoters to highlight their optimum performance under various conditions. The flux improvement achieved during the filtration of the yeast suspensions is further discussed with reasoning behind the behavior of the ceramic membrane. The membrane flux under different conditions of temperature, pressure, feed concentration, and crossflow velocity are recorded over time. Yeast was chosen as a suitable foulant because it created "external fouling", which could be controlled by the appropriate hydrodynamics.

EXPERIMENTAL

Membrane

A single pass Microfiltration Membrane with an O.D of 12 mm and an I.D of 10 mm. It is in a tubular form and made of alumina (70%), zirconia (25%) and yttria (5%). It is 21 cm long and has a nominal pore size of 0.5 microns as shown in Fig. 1. Therefore, its overall filtration area is 62.84 cm^2. The membrane was between 11 and 13 g in weight and was suspended horizontally in the membrane module.

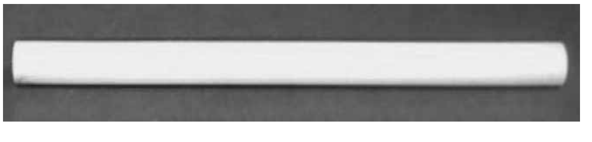

Figure 1. Ceramic microfiltration membrane.

Apparatus and Techniques

The microfiltration experiments and investigations were carried out using the bench scale membrane rig as shown below in Fig. 2. The filtration rig is composed of a stainless steel jacketed feed/recirculation tank or process vessel (SS316/SS304) (700 ml), a positive displacement gear pump (SS316/PEEK mod, a rotameter, valves and a tubular membrane housing that hosts the single layer tubular membrane. The piping that connects the whole rig is made from SS316/SS304 and valves were of the swagelock type. The size/weight of the bench-scale rig is [W-290 $*$ L-340 $*$ H-430 mm, 16 kg]. The tangential flow rate through the membrane was ensured by the pump for both the filtration of yeast suspensions and for the cleaning protocols employed to restore the membrane PWF. (Flowrate varies from 0 L/min (minimum) to 3 L/min (maximum). The volumetric feed flowrate through the module is controlled by adjusting the speed setting on the pump (variable speed controller) and adjusting the regulation valve.

The apparatus was designed to be able to provide crossflow velocities in the range of 0.2 L/min to 2.6 L/min within the pressure range of 0.2 bar to 3 bar and at 1.4 L/min to 2 L/min at very low pressures (0.2–0.6 bar) for cleaning. The experimental data measurements were made via a digital flowmeter (crossflow velocity), chilling unit connected to the jacketed vessel to alter temperature between 20°C and 60°C, pressure gauges for pressure readings and a stop watch to monitor the flow of permeate through the membrane. The crossflow rate was altered via the pump speed

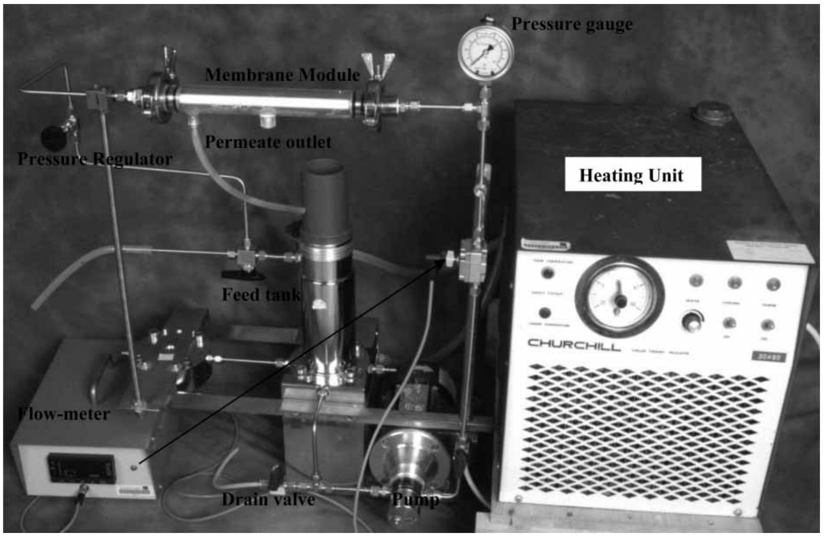

Figure 2. Membrane Rig with tubular membrane module.

connected to a variable speed controller and by means of a control valve located downstream of the membrane and the variable flow of the recirculation pump. The rig arrangement was designed to be able to provide crossflow velocities from 0.6 L/min to 3.5 L/min with system pressures of between 0.3 bar and 8 bar. A constant temperature of 25°C was used in all the experiments except where the temperature was the variable. This temperature is comparable with those that have been employed by other researchers that have worked with yeast suspensions. During the filtration runs, the temperature of the feed suspension was kept at 25°C plus or minus 1°C. Temperature control was attained by passing water, from a Churchill chilling/heating unit (20°C–60°C) and adjusting the temperature as required. The jacket then heated up and cooled down as required.

Turbulence Promoters

Three types of turbulence promoters were used with different pitch lengths of 7 mm, 10 mm and 14 mm as shown in Fig. 3 below. They were made in the workshop at the University of Nottingham and are made of brass with winding helical threads. They are all 23 cm in length and have a diameter of 0.9 cm. They are inserted into the membrane and the membrane is placed in the module that houses the membrane. The inserts were made to have a different number of turns over the whole length. These turbulence promoters were centrally supported inside the membrane and also with circular supports placed in the housing of the module. This was required to stop the swirls from moving within the membrane. It was also established that no additional pressure drop was created by the presence of the supports.

The introduction of the turbulence promoters in the ceramic tubular membrane caused quite a reduction in the crossflow velocity for the same pressure applied and a higher pressure drop for the same inlet flow rate. In order to have a direct comparison of the membrane performance with and without the swirl inserts, the flowrate was adjusted via the pressure regulator and variable speed controller so that the hydraulic dissipated power to the was the same for each system. It should also be noted that the

Figure 3. (a) Pitch length = 7 mm, (b) Pitch length = 10 mm and (c) Pitch length = 14 mm.

insertion of the swirl inserts reduced the value of the equivalent hydraulic diameter.

Yeast Suspension

Yeast comprises of almost spherical particles which usually have a mean diameter of approximately 5 microns with a range from 2.5 to 6 microns (23, 24). The yeast suspension that was used during the experiments was prepared freshly by adding 1 g of yeast granules in 1 L of sugar solution (10 g/L). The suspension was cultured in a fan assisted oven for 18 hours and used as a stock solution. The temperature in the oven was maintained at 37°C and once removed from the oven, it was kept at below 21°C to discourage any additional growth. Yeast microfiltration is of practical importance, as yeast is one of the most important hosts of genetic modification for bio-product manufacture and also used for beer and wine production. Hence, yeast is often used to assess the microfiltration performance.

Reagents

Sodium hydroxide (0.1 M) (Fischer Scientific) and Nitric acid (0.1 M) (BDH Laboratory Supplies, 69%) were used to change the pH of the solutions. Sodium hypochlorite was obtained from BDH Chemicals Ltd and was used as a second cleaning step to remove any layer of caustic solution after the first cleaning step.

Cleaning Agents

The cleaning protocol that was employed with the filtration rig was a three stage cleaning using:

- 1% NaOH solution through the rig at a pressure of 0.3 bar, CFV of 1.7 L/min and a temperature of 50°C for 60 minutes.
- Rinsing/Flushing with 5 L of deionized water for 10 minutes to clean any trace of caustic in the system at a pressure of 0.5 bar, CFV of 2 L/min.
- 2% Sodium hypochlorite solution through the rig at a pressure of 0.3 bar, CFV of 1.7 L/min and a temperature of 50°C for 45–60 minutes.
- Rinsing/Flushing with 5 L of deionized water for 10 minutes to clean any trace of hypochlorite in the system at a pressure of 0.5 bar, CFV of 2 L/min. Sodium hypochlorite is used as an intermediate step between the caustic wash and the acid wash so as to eliminate the occurrence of a reaction between acid and alkali.

- 2% Nitric acid wash through the rig at a pressure of 0.3 bar, CFV of 1.7–1.8 L/min and a temperature of 50°C for 60 minutes.
- Final Rinsing/Flushing with 5 L of deionized water for 10 minutes to clean any trace of acid in the system.

This cleaning protocol was adapted and modified to suit the membrane and the rig from a previous protocol used by (25). All the agents are compatible with the ceramic membrane and industrially relevant. Sodium hydroxide has the ability to saponify fats and solubilise proteins to some extent. There have been various investigations demonstrating the effectiveness and efficiency of NaOH in removing whey protein deposits formed on MF membranes (26, 27). Acids on the other hand dissolve inorganic salts or oxide films and are essential for the removal of minerals.

EXPERIMENTAL APPROACH

The experimental flux decline during the microfiltration of yeast suspension was determined by measuring the volume of the permeate samples collected in a 50 ml measuring cylinder. The first collection was done after one minute and subsequent collections were done every five minutes. The reason was for the permeate flow to stabilize and level off within the membrane module. A known concentration of yeast suspension was introduced into the feed recirculation tank and heated up to 25°C and maintained at that temperature. During filtration, the flow rate and pressure were monitored and controlled with very slight fluctuations due to the voltage fluctuation. Permeate was collected every five minutes and the time taken to collect 50 ml was recorded. After this, the system was rinsed thoroughly with water and the PWF was taken to determine the fouling on the membrane. Each fouling and cleaning cycle consisted of 10 stages: Initial PWF, Fouling experiment, First Water Rinse, NaOH Cleaning, Second Water Rinse, Hypochlorite Cleaning, Third Water Rinse, Nitric Acid Cleaning, Final Water Rinse, and Final PWF. In common with industrial practice, each step was conducted under a turbulent flow regime and the thinking behind this is to encourage a scouring action of the surface. The inserts were removed once filtration was over and the cleaning was carried out without the inserts.

RESULTS AND DISCUSSION

The objectives of the investigation were to study the effects of using static turbulence promoters during microfiltration of yeast suspensions and compare the flux values of the three different promoters and also the flux values without the turbulence promoters. The behavior of the ceramic membranes is also monitored during filtration and cleaning. The analysis of the experimental results and data involves an assumption that the membrane is 100% clean after cleaning and rinsing. The flux values during subsequent experiments are relative to the “clean” membrane. The values of the membrane flux with time are taken relative to the value of the PWF before filtration.

Pressure Effects on Membrane Flux

The effects of pressure changes on membrane flux were investigated over a range between 1 bar and 2.5 bar with a fixed feed concentration and temperature. Different crossflow velocities were used and the results are documented below.

The permeate flux decreases with time at all the pressure values studied and levels off during the time frame of the experiment. The flux remains quite constant at a pressure of 0.5 bar and this shows that at a pressure of 0.5 bar, the fouling is almost preventable and so it is probably convenient to operate an industrial membrane at a very low pressure. Also, this result is in line with the results by Ghaffour et al., 2004 (28) who noticed a considerable level flux at 0.5 bar. At a pressure of 2 bar, we can see that there is now a considerable decrease in the flux more than at lower pressure values. This shows that the rate of particle deposition on the membrane surface is increasing and fouling is beginning to occur. At 2.5 bar, for both flowrates studied, the flux curves are more pronounced and they show a very sharp decline to low values throughout the experiment. This is reflective of the presence of severe fouling experienced at such high pressures. The yeast particles are been pushed into the membrane pores and deep into the membrane surface, thus increasing the resistance of permeate flow and reducing the porosity of the cake layer.

As the pressure increases, there is a noticeable increase in the flux values and also that increasing the crossflow rate increases the flux through the membrane up to certain pressures. At a pressure of 2 bar, the initial flux is higher at 2 L/min than at 1.2 L/min but the final flux value is higher at 1.2 L/min. Also, at 2.5 bar, the Membrane Flux values are higher for the lower flowrate of 1.2 L/min and from Fig. 4b, we can see that the initial flux at 2.5 bar is about 12% higher for 1.2 L/min as compared to the flux at 2 L/min. The final flux values also show a 25% increase for the lower flowrate. This is because at higher pressures at high flowrates, there is very high turbulence within the membrane walls and so there is less residence time for the permeate to be realized. This is why the flux at high pressures is higher at lower flowrates than at higher flowrates in this study.

The driving force is increased and so there is an initial increase in the permeate flux but as the cake layer is increased on the membrane surface, the yeast particles are being pushed further into the pores of the membrane, thus lowering performance and increasing fouling. Up to 1.5 bar, the

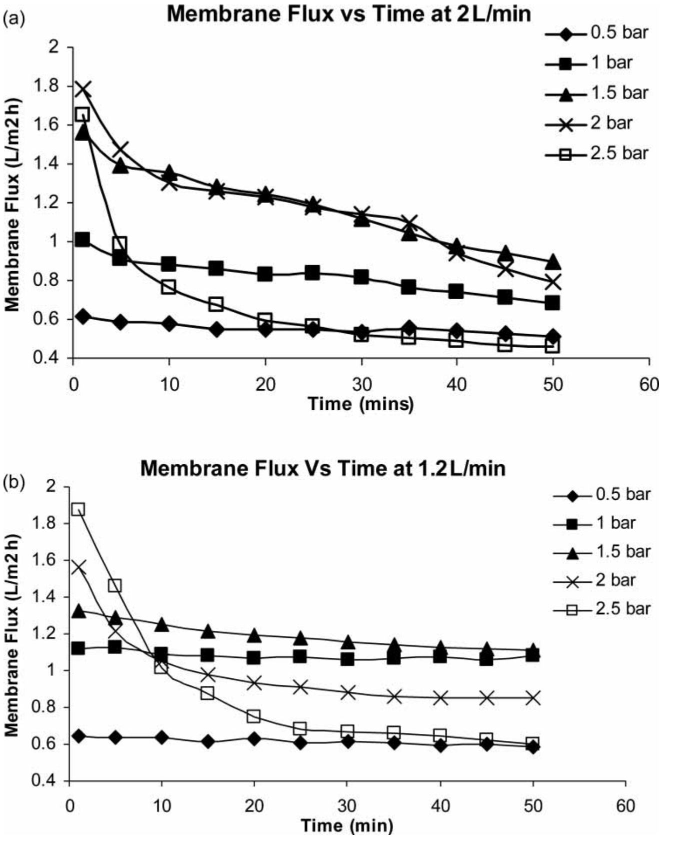

Figure 4. Flux decline curves for yeast suspensions at different pressure values at a crossflow velocity of (a) 2 L/min and (b) 1.2 L/min; 25°C.

relationship of increasing flux with flowrate and pressure is true within this research but at 2 bar, the relationship is altered and the flux begins to decline sharply.

Effects of the Promoters on Flux Values at Different Flowrates (Pressure)

The graphs above show the rate of increase in flux values with an increase in pressure when the Turbulence promoters are used under different flowrates. They show a progressive increase in flux values with increasing pressure. The higher driving force shows a progressive flux increase unlike the results without a swirl insert, which showed that at a pressure of 2.5 bar, there was an initial high flux but a sharp decline to a very low flux value below that of the flux values at 0.5 bar. Membrane flux increases with pressure for all the flowrates at the different pressures that were studied.

From Fig. 5a, it can be concluded that there is a considerable increase in Membrane Flux from the use of promoters with different pitch lengths at the given pressure. The promoter with a pitch length of 14 mm gave the highest improvement in flux with an initial flux increase of 17% and a final flux improvement of 140%. The other inserts also give very considerable improvements when compared to flux without promoters. There were also similar results experienced for the different pressure ranges studied except at 1 bar. This is because at 1 bar, there was not enough pressure to force the fluid over the helical groves of the promoter, thus impeding the flow of fluid through the membrane, hence the permeate flux realized was less than normal.

When the helical baffle is inserted in the tubular membrane, the flow increases at the membrane surface and the feed fluid flow becomes constricted. This means that the area of the flow becomes much reduced. When this happens, the surface area reduction ultimately causes the average fluid velocity to be greatly increased. The fluid then gains momentum and it flows faster, thus increasing the shear rate near the membrane wall. A rapid flow at the membrane surface will reduce the effects of concentration polarization in membrane systems as quoted by Sablani et al. 2001 (29).

The introduction of the promoters caused large reductions in the flow section and a major rotational component. This rotational component creates turbulence that scours the surface of the membrane. The flow field generated by the promoters probably scours the surface of the membrane more than without a promoter. The particle deposition rate thus decreased in the presence of the promoters as observed by Gupta et al. 1995 (8). The filter cake formation is reduced considerably with the use of turbulence promoters, which simultaneously changes the flow field. The scouring action directly removes the deposited particles from the surface of the membrane. This increases the mass transfer away from the surface, thus reducing concentration polarization. When the surface concentration is reduced, permeate easily penetrates the membrane.

From Fig. 5b above, the promoter with the largest pitch length of 14 mm showed the highest flux improvement of up to 7% for the initial flux and up to 60% for the final flux. However, at the flowrate of 1.5 L/min, there was a slight decrease in flux enhancement with the promoter of pitch length 7 mm. This was the promoter with the tightest pitch length and so it was almost identical to a rod insert, which did not have enough helical flow to disrupt the foulant deposited on the membrane surface. Similar results were also obtained at the various pressures studied except below 1 bar.

From Fig. 5c, it can be seen that at the lowest flowrate of 1.2 L/min, the promoter with the highest pitch length of 14 mm was the most effective in enhancing permeate flux through the membrane. An initial flux enhancement of 15% was realized with P = 14 mm and a final flux enhancement of over 50% was realized. The other promoters of varying pitch lengths also

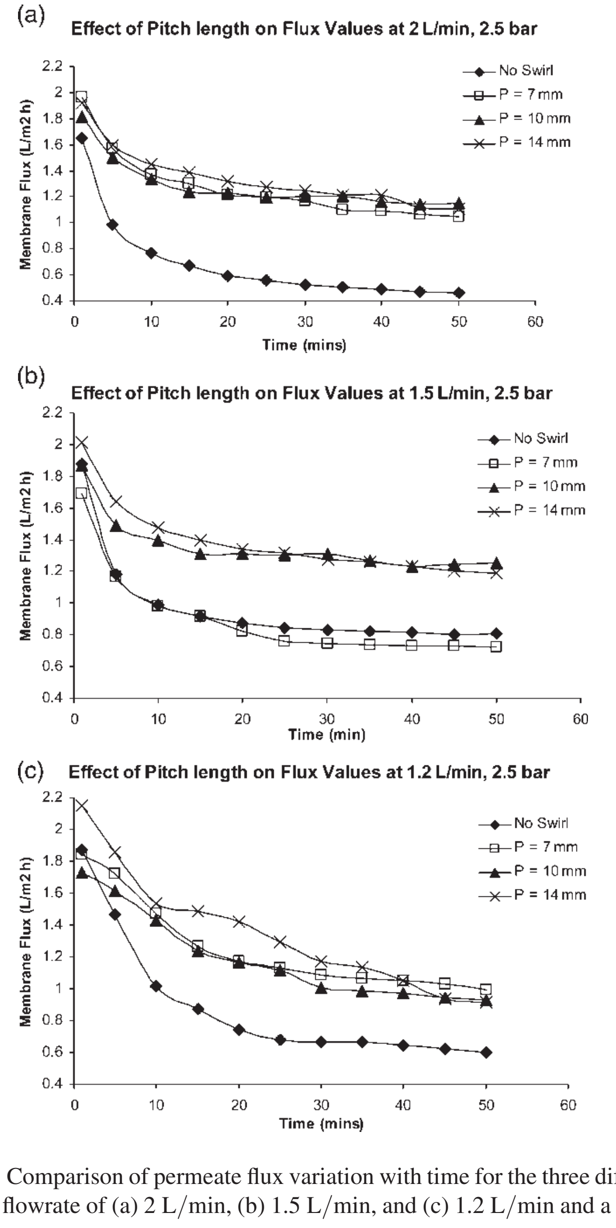

Figure 5. Comparison of permeate flux variation with time for the three different promoters at a flowrate of (a) 2 L/min, (b) 1.5 L/min, and (c) 1.2 L/min and a pressure of 2.5 bar.

showed great final flux improvements with P = 7 mm showing up to 50% and P = 10 mm showing over 50%. As regards a comparison of the three promoters, P = 14 mm showed the highest initial improvement and P = 7 mm showed the highest final improvement. During experiments at the lowest flowrate studied, there was flux improvement for all pressures studied except below 1 bar.

Concentration Effects on Membrane Flux

The graphs show the trend that the higher the feed concentration, the lower the membranes flux. From Fig 6a, it can be seen that 0.01 g/L has the highest overall membrane flux and 0.04 g/L has the lowest membrane flux. As expected, as the concentration increases, the flux decreases, particularly at high pressures. At lower feed concentrations, particularly in the range that the experiments were carried out at, increased pressure values result in increased flux values. When the feed concentration is further increased, an increased pressure would result in membrane flux reduction. This observed behavior during yeast suspension microfiltration is due to cake formation and membrane fouling. At a higher feed concentration, a cake layer is more likely and will form faster. This provides additional resistance to filtration. There is no advantage to operate microfiltration at higher pressures when feed concentration is high. It should be run at low pressures so as to have a higher permeate flux.

Figure 6b shows that at a higher flowrate of 1.8 L/min, the feed concentrations of 0.01 and 0.02 g/L showed the highest flux values, which tie in with the relationship of higher flux values for low feed concentrations. As the concentrations are increased, at a higher flow rate, 0.05 g/L and 0.04 g/L experience high flux values as well and this is probably due to the increased viscosity of the suspensions at high feed concentrations. It can be argued that the higher viscosity would create a higher shear stress, which would eventually be large enough to alter the cake layer that builds up to inhibit filtration at low concentrations. Also, according to Ho et al. 1992, the author reports that specific cake resistance decreases with an increase in feed concentration. This is due to the theory that the greater the concentration the smaller will be the average distance between the particles and the smaller will be the tendency for the particles to be drawn into the streamlines directed towards the open pores (30).

Effects of the Promoters on Flux Values at Different Flowrates (Concentration)

The membrane flux values for all the promoters have been compared and the degree of flux enhancement is discussed below. At the highest flowrate of 2.5 L/min, filtering a 0.02 g/L feed concentration yielded flux enhancements for all the turbulence promoters investigated. The experiment without a promoter experienced a steep membrane flux decline but with the introduction of promoters, there were certain degrees of flux enhancement. P = 7 mm showed the lowest degree of enhancement with an initial flux enhancement

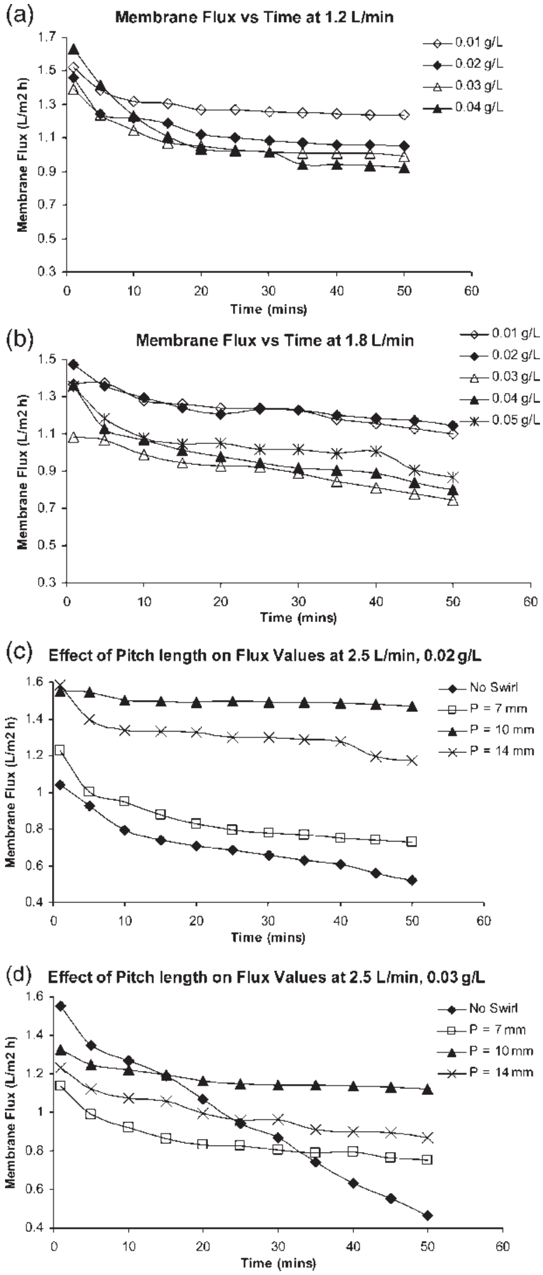

Figure 6. Flux decline curves for yeast suspensions at different feed concentration values at a crossflow velocity of (a) 1.2 L/min, (b) 1.8 L/min; 25°C; (c) and (d) Comparison of permeate flux variation with time for the three different promoters at a flowrate of 2.5 L/min and a pressure of 1.5 bar.

of 18% compared to that of the empty membrane and a final flux enhancement of up to 40%. In most cases, the promoter with the smallest pitch length shows the lowest flux improvement due to the similarity to a cylindrical insert, which restricts the flow over the "narrow" helices and reduces the flow through the membrane. On the other hand, the promoter with the pitch length of 10 mm showed the largest initial flux enhancement with up to 50% and a final flux improvement up to 180%.

In Fig. 6d, the turbulence promoters had a positive effect on membrane flux and it shows that there was no improvement at the beginning of the experiment but after 10 minutes of microfiltration, there was improvement. The promoters maintained the membrane flux to values above those of the empty tube and reduced the degree of fouling. Similar degrees of enhancement were realized in this experiment, with P = 10 mm showing the largest improvement and P = 7 mm showing the lowest improvement. There was a reduction in initial flux up to 26% for P = 7 mm and an improvement of up to 140% for the final flux for P = 10 mm.

Temperature Effects on Membrane Flux

The effects of temperature on the microfiltration of yeast suspensions have shown an inconsistency in trends using an empty tubular membrane. The decline at certain temperatures was higher than at others and this showed that with a constant pressure as the driving force, the membrane showed a linear decline in permeate flux at different temperatures.

Running the experiments with the turbulence promoters to determine the effects of temperature and the rates of enhancement of the turbulence promoters on membrane flux showed a certain consistency in the results. Flux was not necessarily improved at all over the temperature range studied and also with any of the promoters within the ceramic membrane. On the contrary, membrane flux was reduced for all cases on filtration with temperature.

From Fig. 7a, we can see that membrane flux increased with temperature up to 45°C but there was a steep decrease in membrane flux and there is the possibility that the yeast suspension becomes distorted and undergoes denaturation. This means that the structure is broken up and so there is less permeate realized through the membrane surface.

Effects of the Promoters on Flux Values at different flowrates (Temperature)

From the graphs below showing the comparison of turbulence promoters, it is clear to see that the turbulence promoters had no positive effect on flux enhancement for any of the temperature conditions. The reasoning behind the lack of enhancement for all the temperatures is that the yeast suspension

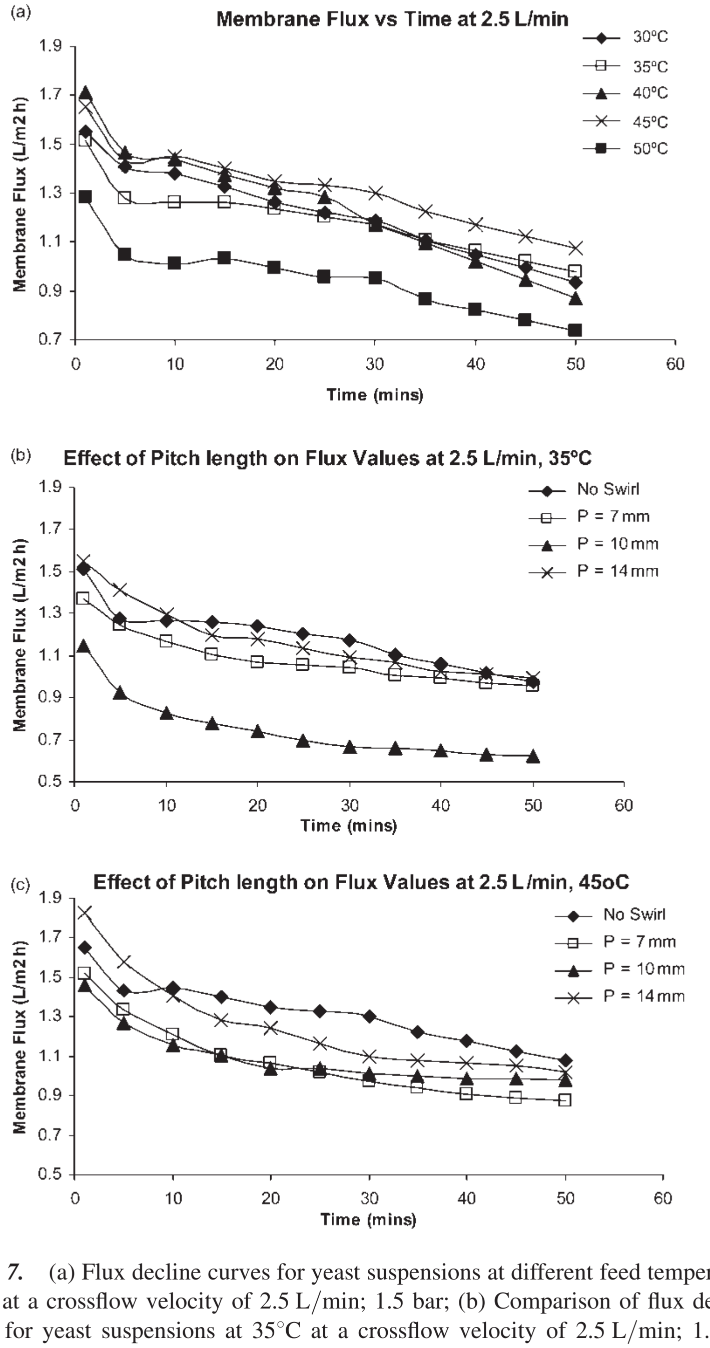

Figure 7. (a) Flux decline curves for yeast suspensions at different feed temperature values at a crossflow velocity of 2.5 L/min; 1.5 bar; (b) Comparison of flux decline curves for yeast suspensions at 35°C at a crossflow velocity of 2.5 L/min; 1.5 bar for three turbulence promoters; (c) Comparison of flux decline curves for yeast suspensions at 45°C at a crossflow velocity of 2.5 L/min; 1.5 bar for three turbulence promoters.

at higher temperatures undergoes denaturation and the promoters further distort the suspensions within the membrane walls. This blocks the pores with more particles and prevents the smooth transition of the permeate within the pores of the membrane.

CONCLUSIONS

The experiments with the turbulence promoters were found to be relatively simple due to the ease of removal and input into the tubular membrane. The inserts generally improved the membrane performance and increased permeate flux under certain conditions including pressure and concentration changes. Temperature did not really have a positive effect on the turbulence promoter experiments as membrane flux decreased considerably with temperature. This is attributed to the probable softening and denaturation of the yeast suspensions at higher temperatures and also the ease of its adhesion unto the walls of the membrane. It was more beneficial to run the experiments with a smooth membrane under increased temperature. The enhancement in flux in some cases was up to 140% and was obtained without any additional equipment. The turbulence promoter with the longest pitch length showed the better improvement compared to the other two in most of the experiments. Also, it can be concluded that the configurations that include turbulence promoters inserted into a tubular membrane are very effective in roles that utilize lower crossflow velocities.

LIST OF ABBREVIATIONS

CFV	Crossflow Velocity
I.D	Inner Diameter
MF	Microfiltration
NF	Nanofiltration
O.D	Outside Diameter
PWF	Pure Water Flux
SS	Stainless Steel
UF	Ultrafiltration

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