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Experimental Investigation on the Separation of Bentonite using Ceramic Membranes: Effect of Turbulence Promoters

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Abstract: The static turbulence promoters presented in this work are designed to enhance filtration within tubular ceramic membranes of 0.5 micron pore size. Permeate flux enhancement still remains a topical problem during tangential crossflow filtration. The decline in flux with time is due to the usual phenomena of concentration polarization and membrane fouling, operating parameters including the system pressures, feed composition, membrane type and configuration, and the hydrodynamics within the membrane module. Solute accumulates on the membrane surface and forms a high concentration gel layer, thus increasing the effective membrane thickness and reduces its hydraulic permeability. Turbulence promoters of varying pitch lengths have been incorporated into the work to ultimately reduce the deposition of bentonite particles on the membrane surface during microfiltration. Yeast suspensions have previously been used as feed suspensions in order to compare the effectiveness of the turbulence promoters with an organic foulant. The objective of this work was to investigate the influence of static promoter geometry on flux sustainability enhancement during bentonite suspension filtration. All experiments have been conducted on a tubular ceramic membrane and the experimental membrane rig as shown in this paper. The effects of feed concentration, feed temperature, system pressures, and crossflow rates on the membrane flux sustainability were investigated. It was found that the promoters greatly improved flux sustainability and membrane efficiency over time and in some cases, a loss of 3% in membrane efficiency was realized

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with turbulence promoters at higher feed temperatures. The use of the turbulence promoter caused a large scouring of the membrane surface and membrane cleaning was significantly improved compared to the experiments without the promoters.

Keywords: Flux sustainability, tubular membranes, static turbulence promoters, microfiltration

INTRODUCTION

Crossflow microfiltration is an important membrane separation process with a growing number of applications in different industrial sectors including food and bio-technology, pharmaceutical, construction and petrochemical industries. The use of membranes in environmental engineering has been on the increase over the last few years and they are applied on a large scale for a wide range of applications within several industries (1). There have been some China factories that have produced effluents rich in clay and glaze particles and traditionally, they have gone untreated to the nearest water courses. However, most European countries have tightened their legislation as regards the environmental emissions to land and water bodies. The EPA in the UK has ordered companies to cease to discharge clay and other building material effluents into rivers as these could obstruct the view of the fish and sea creatures in the turbid surroundings caused by factory effluents. The solid particles would also cause a blockage and clogging of the fish gills, which would cause breathing difficulties for the fish (1). Clay minerals are extensively used in a wide range of applications. They are a key component in the formulation of ceramic products, cement, drilling fluids, moulding sands, paints and paper, amongst others (2). Bentonite clays are also widely used as thickening agents in many industrial preparations such as drilling fluids, cement, paint, paper, cosmetics, and pharmaceuticals (3). Bentonite clays are the most used materials in the petroleum industry for the preparation of drilling fluids. They are used due to their ability to present particular rheological properties. Equally important is their ability to form a cake on the walls of the rock formation, which prevents the collapse of the pit walls (4). The knowledge of the filtration properties and particularly, of permeability, is very important and can ascertain if a clay is suitable or not for use in the preparation of drilling fluids. Drilling fluids are primarily water-bentonite suspensions. They are important for the oil, gas, and geothermal drilling industry because they perform many functions like transporting rock cuttings to surface, lubricating the drill bit, applying hydrostatic pressure in the well bore to ensure well safety and minimize fluid loss across permeable formations by forming a filter cake on the walls of the well bore (5).

The use of static turbulence promoters as an effective technique for reduction of concentration polarization and membrane fouling in crossflow membrane filtration has been investigated relatively often (6). Flux enhancement and flux control under laminar flow conditions can be achieved by generating well-defined secondary-flow structures (7). The use of baffles to enhance microfiltration has only been successful when the radial velocities are high, which leads to high Reynolds numbers and the flow becomes turbulent (8). Different shapes of static turbulence promoters such as static rods, spiral wire, metal grills, disc and doughnut shape inserts, and others have been extensively used during microfiltration and ultrafiltration with different fluids and with or without superimposing the pulsating flow (9). However, pressure loss induced by the presence of the static turbulence promoter increased the power required for fluid circulation as mentioned by (10), leading to increased energy consumption. Moreover, the increase in pressure drop by using a static turbulence promoter can cause significant variation of transmembrane pressure along the membrane length. Some of the mechanisms of turbulence promoters have been discussed previously in parallel work using yeast suspensions.

The main aim of this work is to carry out a series of microfiltration experiments to determine the effects of turbulence promoter geometry on flux sustainability enhancement and microfiltration performance using bentonite suspensions. Yeast suspensions were used in previous experiments using the same turbulence promoters and experimental rig described in the next section (11, 12). The method employed was to use promoters of different pitch lengths applied internally to tubular ceramic membranes with nominal pore size of 0.5 microns to generate secondary flows. Vortices can be generated from a sudden flow expansion or due to centrifugal instabilities. The helical thread flow promoters combine these features and ultimately generate effective mixing. The basic filtration properties of the empty membrane are analyzed under various operating conditions and are compared with filtration properties using three different turbulence promoters. This paper will highlight some of the fundamental differences in membrane performance during filtration cycles with and without promoters. The graphical data was analyzed in terms of percentage increments in flux compared to the experiments without turbulence promoters.

MATERIALS AND METHODS

Membranes

The membranes used are tubular ceramic membranes, which were obtained from Sterilox. They are made of alumina (70%), zirconia (25%) and yttria (5%), with a nominal pore size of 0.5μm. The tube lengths are approximately 21 cm in length (L = membrane length = 21 cm), with an outer diameter (O.D) of 1.2 cm and an internal diameter (I.D) of 1 cm. These membranes were chosen for their chemical resistance and also for their resistance to the high temperatures, high mechanical strength and pH values of the cleaning protocols. The ceramic membranes were also liable to generate both internal and external fouling as is frequently encountered in biotechnology and food processing applications. There was no accompanying information on the working temperatures, cleaning regimes, and maximum working pressures for the ceramic membranes. Trial and error methods were needed to come up with satisfactory conditions for the filtration experiments. The overall filtration area produced by the membrane is $6.28 \times 10^{-3}\,m^2 = 62.84\,cm^2$. SEM analysis of the membrane was required to work out the effective pore size distribution and the porosity of the membrane. It was found that it has a porosity of 50% and a nominal pore size of 5 microns as shown in Fig. 1 below. The experimental rig was specially designed and modified to house the tubular ceramic membranes as shown in Fig. 2.

Experimental Rig and Conditions

All filtration experiments were carried out using the experimental rig before and after modifications. Figures 2a–b show schematic diagram of the rig. The effect of the turbulence promotion on microfiltration performance and flux sustainability was investigated using the static turbulence promoters shown in Fig. 3. The experimental investigations were carried out using the modified membrane rig shown in Fig. 2b. It consists of a stainless steel jacketed feed/recirculation tank (SS316/SS304), a positive displacement gear pump (SS316/PEEK mod), a rotameter, valves, and a tubular membrane housing that hosts the single channel tubular membrane below. The modified unit has a plastic extension

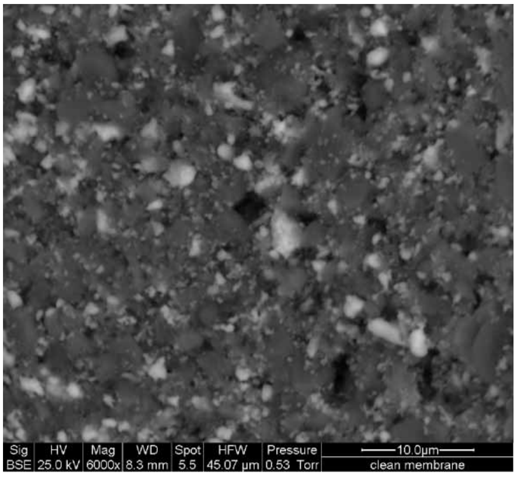

Figure 1. SEM image of the 0.5 micron tubular ceramic membrane.

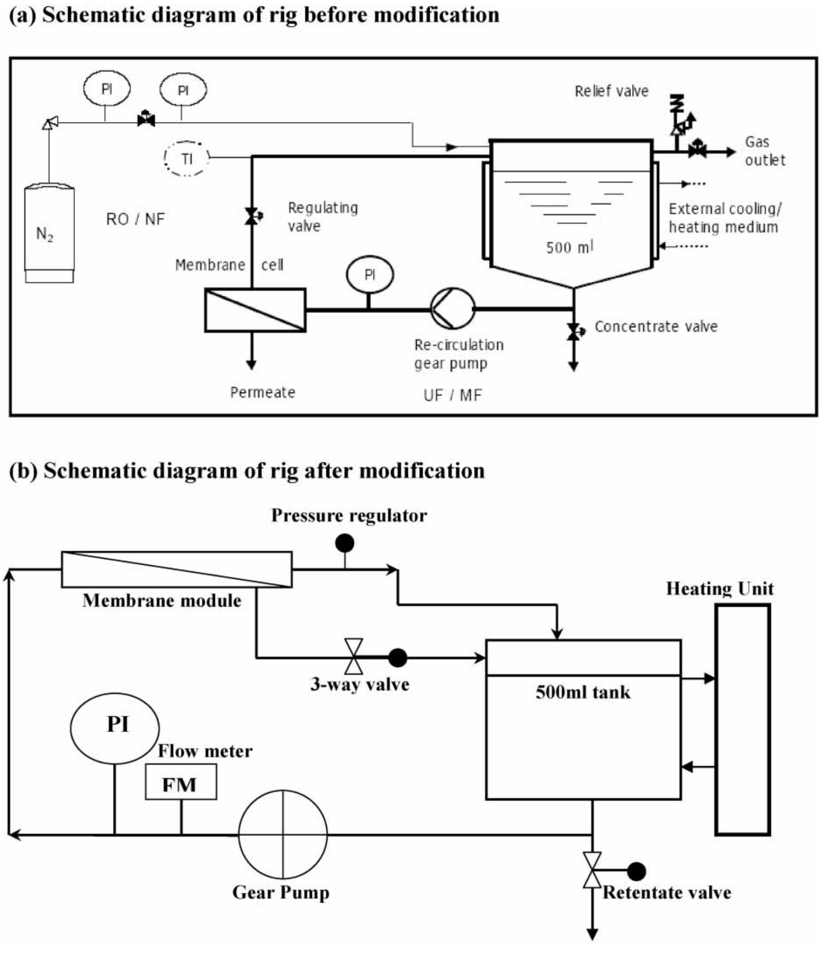

Figure 2. Original and modified cross-flow rig.

at the top of the feed tank to accommodate more test solution and also to operate the system and minimize the splashing that occurs when the retentate is returned to the feed tank at higher velocities. There is also a tubular membrane housing as shown below that has been attached to the pipe-work to accommodate a single tubular membrane shown below in Fig. 2a. The housing has been designed in a way to recover permeate via a hose attached to the bottom of the housing shown in Fig. 2a. The additional piping that connects the different parts of the rig was also made from SS316/SS304 and valves were of the swagelock type. The tangential flowrate through the membrane is ensured by the pump for both the filtration of bentonite suspensions and also for the cleaning protocols employed to restore the pure water flux (PWF) of the membrane. The allowable flowrate is between 0 L/min to 3 L/min. This

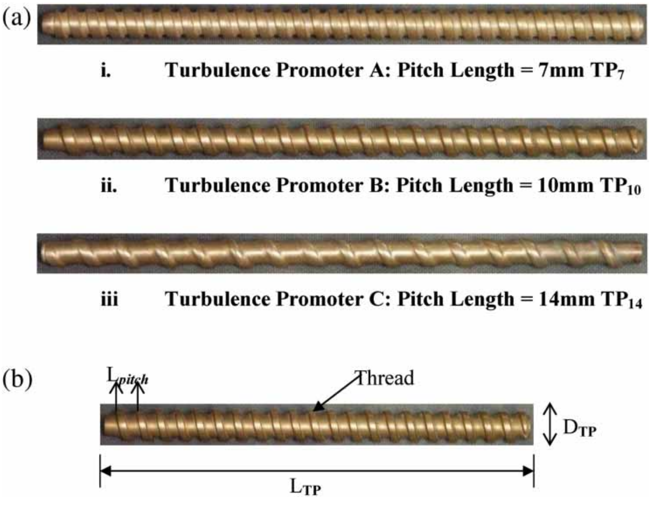

Figure 3. (a) Description of the parts of the static turbulence promoter; (b) Different static turbulence promoters of varying pitch lengths.

volumetric feed flowrate through the module is controlled by adjusting the speed setting on the pump via the variable speed controller and adjusting the regulation valve located downstream of the membrane module. The configuration of the modified rig is in a recycle mode as shown below. It shows the retentate flowing back into the feed tank in order to maintain a uniform concentration of suspension in the feed tank. The flowrate for filtration experiments are in the range of 1.1 L/min to 2.6 L/min at pressures of 1 bar up to 2.5 bar and 1.4 L/min to 2 L/min for very low pressures (0.2–0.5 bar) for cleaning protocols. Crossflow velocity measurements were made via a digital flowmeter connected to the inlet feed of the rig and a chilling unit connected to the jacketed vessel was used to alter the temperature of the feed suspension between 20°C and 60°C as shown in the modified diagram. Temperature control was efficiently maintained by passing a mixture of water and glycol from the heater unit through the jacket of the vessel. The jacket then heated up and cooled down as required. A pressure gauge mounted on the feed inlet side of the rig is used to monitor the pressure readings during the experiments and cleaning protocols. A constant temperature of 25°C was used in all the experiments except where the temperature was the variable. The temperature that was chosen is comparable to those that have been employed by other researchers that have worked with bentonite suspensions. There is also a three way valve that is used to divert the retentate back to the feed tank and also to carry out a flushing of the system with water, where the water is introduced through the top of the feed vessel and pumped out through the three way valve to drain. The membrane module was designed in-house and consists of a perspex casing connected to the fittings through which the tubular membrane sits in. The module was connected via diary fittings unto the pipe work on the membrane rig shown in Fig. 2a. The permeate flux was calculated from the time needed to collect 50 mL of permeate. The efficiency of the turbulence promoters was determined as a direct improvement in membrane efficiency from the flux vs time graphs. The membrane was cleaned by immersing the membrane module with the ceramic membrane into an ultrasonic bath with a mixture of sodium dodecyl sulphate and caustic solution. Cleaning was carried out prior to each experiment until the water flux of the membrane was restored to a value close to its original state. The pure water flux of the membrane was measured at 25°C at a pressure of 1 bar to determine the time taken to recover 50 mL of permeate.

Bentonite Suspension

The feed used throughout the experiments were bentonite suspensions of different concentrations ranging from 0.03 g/L to 0.1 g/L. Bentonite was stored at room temperature and away from moisture to avoid any change in structure and any swelling. Specific quantities of bentonite powder were accurately weighed and added to deionised water at room temperature. The resulting suspension was then mixed vigorously for up to 10 minutes using a bench scale high shear mixer (scale of mixer = 5). This was to allow a uniform dispersion of bentonite particles within the suspension and to avoid over-aggregation of the particles prior to the filtration process. As the way of preparation has a great influence on the final state of the suspensions (the degree of dispersity) and thus on the rheological behavior prior to filtration, all the samples were prepared in the same way. There was extra care taken particularly to prevent an attack of the clay structure by avoiding direct contact of acidic or basic compounds with the dry clay powder. The suspension is then introduced into the feed tank and filtration is started. Fresh suspensions were made for each and every experiment to avoid any change to particle sizes and to avoid agglomeration over time.

Turbulence Promoters

There were three different promoters, each having a length of 22.5 cm and a thickness of approximately 0.75 cm. The distinct difference between the promoters is their pitch length as shown in Fig. 3, which is the parameter that is being investigated in relation to membrane flux behaviour for the ceramic membrane. They were manufactured in the workshop at the University of Nottingham (SChEME). They were manufactured using a Colchester center lathe using a single point high speed steel tooling to generate the required form at various pitches. They are also made from brass and have winding helical threads throughout the length of the promoter. The pitch lengths are

Table 1. Characteristics of the used static turbulence promoters

Symbol	P = 7 mm	P = 10 mm	P = 14 mm
Construction material	Brass	Brass	Brass
Diameter (D_{TP}, mm)	7.5	7.5	7.5
Length (L_{TP}, mm)	225	225	225
Pitch length ($L_{pitch,}$ mm)	7	10	14

TP_7 (7 mm), TP_{10} (10 mm), and TP_{14} (14 mm) respectively (Table 1). They are inserted into the tubular ceramic membrane and sit within the membrane in a perspex membrane module. The promoters are also centrally supported in the membrane with fittings within the housing of the module. This was required to stop them from moving within the membrane to cause irregularities in the flux values and also damage to the membrane and the module.

The bentonite suspension, the pure water flux was measured to analyze the irreversible part of fouling. After testing the membranes were cleaned by 20 min ultrasonic stirring with a solution of 1%wt NaOH + 0.2%wt. anionic surfactant SDS (Sodium Dodecyl Sulphate) and the original water permeability was recovered.

Turbulence promoters are used because of their function in creating 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. The promoters help in keeping the particles of the suspension away from the membrane walls via their helical threads. In addition to the helical flow pattern, which establishes a rotational (swirling secondary flows) flow, the periodic alternation of the flow establishes the generation of vortices. These in turn further increase the shear rate in the neighborhood of the membrane surface. This increased shear rate generated by the introduction of the turbulence promoters scours the membrane surface mechanically more than in the case of the empty membrane.

Calculations

The efficiency of the turbulence promoters are calculated directly from the graphs as shown in the results section. They are measured based on the membrane efficiency improvement when using the promoters. Each experiment is considered with a clean membrane of 100% purity i.e., no fouling. The flux ratios are calculated relative to the initial flux value at the start of the experiment after 1 minute. This initial flux value is regarded as 100% and subsequent flux values are divided by the initial value. The degree of improvement in flux sustainability and membrane efficiency with the different turbulence promoters is taken relative to experiments without the promoters. The flux values were calculated for each experiment by the following equation:

$$\text{Amount}-\text{of}-\text{permeate} = 50\,\text{ml} = 0.05\,\text{L}$$

$$\text{Time}-\text{taken} = \left(\frac{\sec s}{60}\right) = \left(\frac{\min\ s}{60}\right) = \text{hours}$$

$$\text{e.g} - \left(35\,\text{s} = \left(\frac{35}{60}\right) = 0.583\ \text{min s} = \left(\frac{0.583}{60}\right) = 9.72 \times 10^{-3}\,\text{hrs}\right)$$

$$\text{Membrane} - \text{Area} = 0.006284\,\text{m}^2$$

$$\therefore \text{Flux} = (\text{L/m}^2\text{h}) = (0.05/(0.006284 \times 0.00972))$$

$$\text{Flux} = 818.59\,\text{L/m}^2\text{h}$$

De-ionized water or the feed suspension is filtered through the membrane and the time taken to collect the permeate in a 50 ml measuring cylinder is measured. Pure water flux J_V and permeate flux J_V are calculated using Equation (2) and (2.1) below:

$$J_V = \left(\frac{V}{A \times t}\right)$$

where J_V is the pure water flux or permeate flux (L/m^2 h), V is the volume of permeate collected (L), A is the effective membrane area and t is the time taken to collect the permeate (hours).

Calculation of Flux Ratios

$$\text{Ratio} = \left(\frac{\text{Initial} - \text{Flux}}{\text{Flux} - \text{value}}\right)$$

$$1\ \text{min} = 235\ \text{L/m}^2\text{h}$$
$$\text{e.g} - (235/235) = 1(\text{Initial} - \text{flux})$$

$$50\ \text{min} = 196.18\ \text{L/m}^2\text{h}$$
$$\text{e.g} - (196.18/235) = 0.83(\text{Final} - \text{Flux})$$

RESULTS AND DISCUSSION

The average particle size for the bentonite suspensions was found to be approximately 2 μm. Thus, the average size of the particles in the feed stream is bigger than the average pore size of the ceramic membrane, which is 0.5 μm. As such, there is the theory that the entire feed particles will be retained at the membrane wall and prevented from passing through the membrane pores. Hence, internal pore blocking and partial pore blocking is not expected to occur but there is the possibility of a few exceptions. Most of the fouling that is expected to occur is due to the filter cake formation on the membrane surface. Microfiltration studies by (13) performed on bentonite clay suspensions showed improved efficiency with helical membranes. The promoters reduce the presence of membrane fouling and by producing a helical flow pattern and generating a secondary flow to combat the formation of a concentrated gel layer immediately above the membrane surface. The helical flow is the pattern of flow that is found along the grooves of the promoter. These helical vortices give rise to instabilities within the feed and consequently mechanically scour the membrane surface. The degree of turbulence generation is greater when using promoters with helical grooves compared to cylindrical inserts because helical vortices enhance mixing between the boundary layer of the membrane and the bulk fluid. The principle of inducing turbulent flow and creating instabilities within the fluid to improve flux sustainability has led to further research on investigating the effect of pitch length of the helical thread on the promoter.

Pressure Effects

The variations of permeate flux sustainability with system pressure (1–2.5 bar) during the microfiltration of bentonite suspensions without the use of turbulence promoters (NTP) is shown in Figs. 4a–c. The experiments were carried out at three different feed flowrates of 2 L/min, 1.5 L/min, and 1.2 L/min with recirculation of permeate. Figures 4a–c clearly show that at all flowrates studied, there was a reduction in flux sustainability and membrane efficiency with increased system pressure from 1 bar to 2.5 bar. For this study, the behavior of the membrane at higher pressures was retarded due to a higher driving force pushing the bentonite particles further unto the membrane surface. However, at higher pressures encountered during microfiltration, linear pressure dependence is halted due to the fact that additional increases in pressure are counteracted by a decrease in the cake porosity on the membrane surface. This is because the additional pressure compresses the cake on the membrane surface. There is also the possibility of increasing the cake thickness due to more deposition of bentonite particles during a transitory increase in flux that follows a pressure increase as described by (14).

It is clear from Fig. 4a that the final membrane efficiency was in the region of 55% when operating at 1 bar, with an initial flux of 285.5 L/m^2 h (J_i) and a final flux of 158.7 L/m^2 h (J_F). (PWF = 337 L/m^2 h at 1 bar). However, as the system pressure is increased, final efficiency values fall to just below 47% (Initial flux = 459 L/m^2 h (J_i); Final flux = 216.1 L/m^2 h (J_F),

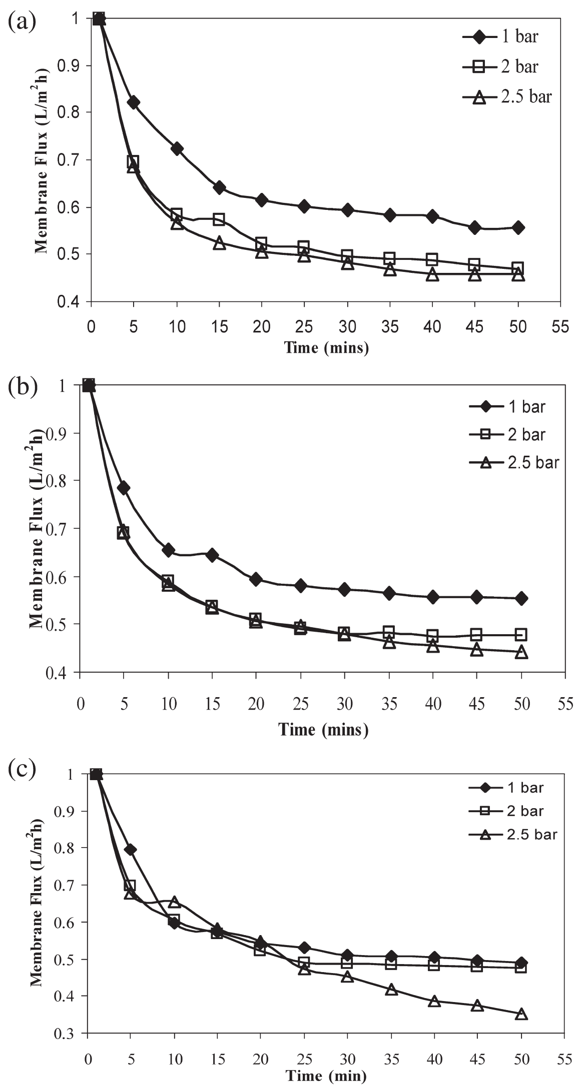

Figure 4. Pressure effects on flux sustainability at a) 2 L/min, b) 1.5 L/min, c) 1.2 L/min.

PWF = 415 L/m^2 h at 1 bar) and 45% (Initial flux = 522 L/m^2 h (J_i); Final flux = 239.4 L/m^2 h (J_F), PWF = 421.2 L/m^2 h at 1 bar) with operations at 2 bar and 2.5 bar. There is a gradual decline in membrane flux sustainability over time for all the pressures studied and it's more pronounced at higher pressures with membrane efficiency after 10 minutes being 72% at 1 bar (Flux = 206.9 L/m^2 h (J_v)), 58.4% at 2 bar (Flux = 268.4 L/m^2 h (J_v)) and

56.8% at 2.5 bar (Flux = 296.7 L/m^2 h (J_v)). The increase in system pressure had positive effects on the permeate flux recovered and negative effects on membrane efficiency as seen in Fig 4a. As pressure increased, the permeate flux realized increased as shown by the flux values associated with the ratios. However, at the high pressure of 2.5 bar, there was initially high flux but it declined through the experiment. After half an hour, membrane efficiency was found to be 59.2% at 1 bar (Flux = 169.2 L/m^2 h (J_v)), 49.4% at 2 bar (Flux = 227 L/m^2 h (J_v)) and 48% at 2.5 bar (Flux = 251.6 L/m^2 h (J_v)). These figures show that the efficiency decreases with the increase in pressure.

Figure 4b shows that membrane flux sustainability was highest at a system pressure of 1 bar with the efficiency reaching a final value of 55.4% (Initial flux = 361 L/m^2 h (J_i), Final flux = 200.2 L/m^2 h (J_F), PWF = 434 L/m^2 h at 1 bar) compared with the value at 2 bar at 47.5% (Initial flux = 488.4 L/m^2 h (J_i); Final flux = 232.4 L/m^2 h (J_F), PWF = 409.2 L/m^2 h at 1 bar) and 2.5 bar at 44.1% (Initial flux = 505.2 L/m^2 h (J_i); Final flux = 223.2 L/m^2 h (J_F), PWF = 421.2 L/m^2 h at 1 bar). These figures show that more permeate was realized initially at a higher pressure but subsequently reduced the membrane efficiency with time. Similar trends of decreasing flux sustainability and membrane efficiency were encountered with increasing system pressures throughout the experiment as shown in Fig. 4b below. At the higher pressures of 2 and 2.5 bar, there was no difference in flux sustainability although they both showed final flux efficiencies of below 50% compared to 55% obtained at 1 bar. As observed at all flowrates, there is a very steep drop in membrane performance and sustainability of flux within the first ten to fifteen minutes of filtration. This is because bentonite suspensions have severe fouling properties as documented in previous work by (15) who used a model suspension of clay (bentonite) and an optical measurement technique to measure the deposit thickness. The final membrane efficiency reduces by almost 45% in all cases studied after 15 minutes of filtration at 2 and 2.5 bar as shown in Figs. 4a–c and this is probably attributed to the deposition of bentonite particles unto the membrane surface from a higher driving force. The mode of fouling at 1.2 L/min as shown in Fig. 4c is similar to those shown in Figs. 4a–b because membrane flux sustainability is shown to be slightly higher at 1 bar, although from the graph at 1.2 L/min, there seems to be no distinct difference in membrane efficiency until towards the end of the experiment. The membrane flux sustainability was almost equal at operating pressures of 1 and 2 bar, with membrane efficiencies showing similar final values at 49% (Initial flux = 399.6 L/m^2 h (J_i), Final flux = 196 L/m^2 h (J_F), PWF = 462 L/m^2 h at 1 bar) and 48% (Initial flux = 485.3 L/m^2 h (J_i); Final flux = 231.2 L/m^2 h (J_F), PWF = 372 L/m^2 h at 1 bar) respectively. It can also be seen that at 2.5 bar, the efficiency of the membrane further reduced at the end of the experiment to a minimum of 35%. The flux sustainability at 2.5 bar suffered a steep decline from approximately half way through the experiment.

Concentration Effects

The effects of feed concentration on flux sustainability without any turbulence generation are shown in Figs. 5a–c. It can be seen clearly from the graphs that an increase in the feed concentration of bentonite causes a considerable reduction in membrane flux sustainability. This is probably due to an increased accumulation of bentonite particles on the membrane surface because there are more particles available for deposition at a higher feed

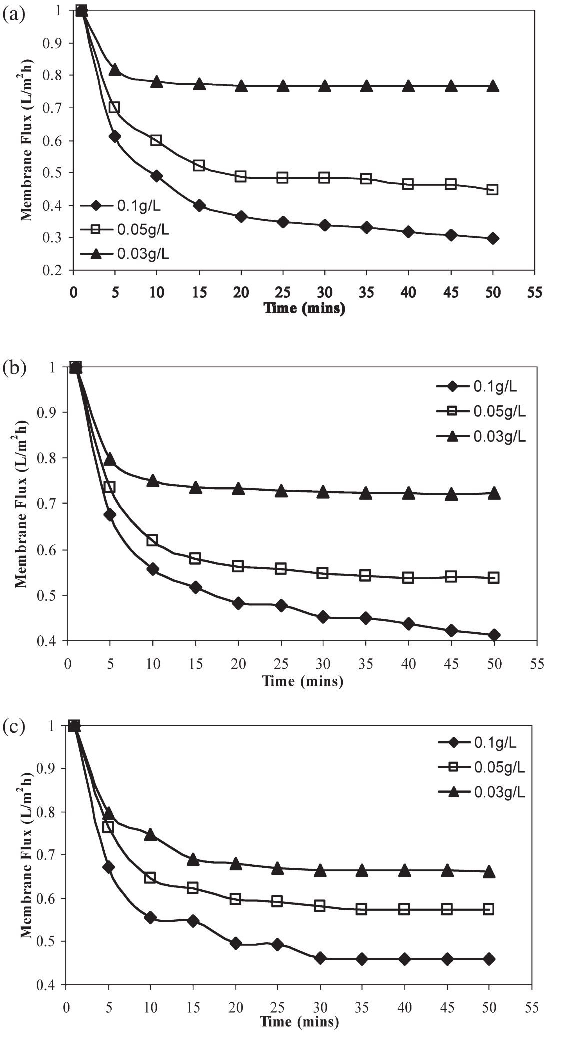

Figure 5. Concentration effects on flux sustainability at a) 2.5 L/min, b) 1.8 L/min, c) 1.2 L/min.

concentration. Three feed concentrations were used throughout these experiments at three different feed flow rates. The sharp decline in flux values at higher feed concentrations is as a result of the deposition of particles on the membrane surface.

At a high flowrate of 2.5 L/min and at a system pressure of 1.5 bar, it can be observed from Fig. 5a that the highest concentration gave the lowest membrane sustainability. 0.1 g/L showed a final membrane efficiency of 30% (Initial flux = 554.8 L/m^2 h (J_i); Final flux = 166 L/m^2 h (J_F), PWF = 774 L/m^2 h at 1 bar) as compared with a higher value of 45% (Initial flux = 497.4 L/m^2 h (J_i); Final flux = 222 L/m^2 h (J_F), PWF = 502.5 L/m^2 h at 1 bar) for 0.05 g/L and the highest value of 77% (Initial flux = 577.1 L/m^2 h (J_i); Final flux = 443 L/m^2 h (J_F), PWF = 520.8 L/m^2 h at 1 bar) for 0.03 g/L. This suggests increased flux sustainability values at lower feed concentrations under a fixed system pressure. This external fouling is the dominant contributor to membrane flux degradation when linear dimensions of the majority of the suspended particles are larger than the membrane pores. This is in tandem with the findings by (16) who used laboratory experiments performed on clay suspensions and the removal of suspended solids and dispersed oil from an aqueous stream to demonstrate this effect. This dominating fouling mechanism was identified through a technique described by (17). As the feed was increased, the viscosity of the suspension increased and this had a negative effect on membrane flux sustainability and subsequently membrane efficiency. At the mid-point of the experiment (25 mins), it can be seen from Fig. 5a that filtration of the 0.03 g/L suspension showed a membrane efficiency of 76% (Flux value = 442 L/m^2 h (J_v), Initial Flux = 577 L/m^2 h (J_i), PWF = 520.8 L/m^2 h at 1 bar), which is equal to the efficiency at 50 mins, showing excellent membrane sustainability, without a loss in membrane performance. With the other concentrations, there was also a near constant flux sustainability after 25 mins. The filtration of 0.05 g/L suspension showed a membrane efficiency of 48% (Flux = 241 L/m^2 h (J_v), Initial Flux = 497.4 L/m^2 h (J_i), PWF = 502.5 L/ m^2 h at 1 bar) and 44% (Flux value = 222 L/m^2 h) for the final efficiency, indicating a 4% loss in membrane efficiency and 0.1 g/L showed 35% (Flux value = 193.8 L/m^2 h, Initial Flux = 554.8 L/m^2 h (J_i), PWF = 774 L/m^2 h at 1 bar), with a final efficiency of 30% (Flux value = 166 L/m^2 h), indicating a 5% loss.

Similar trends were observed at the lower flowrates studied with an increasing feed concentration leading to a lower membrane efficiency. For the flowrate at 1.8 L/min at a feed concentration of 0.1 g/L, there was a considerable decrease in membrane flux sustainability as seen in section 6.5.1. The membrane suffered a loss of up to 60% in efficiency by the end of filtration, indicating severe fouling and high particle deposition. The initial permeate flux was 385.6 L/m^2 h (J_i), which decreased dramatically to 159.2 L/m^2 h (J_F) after 50 minutes (PWF = 454 L/m^2 h at 1 bar). However, during the experiment, there was a gradual rate of increased particle deposition, which ultimately contributed to a loss in flux sustainability. After half an hour of filtration, the membrane had reached 45% efficiency (Flux value = 174.5 L/m^2 h (J_v)). This sharp and steady decrease in flux under constant pressure indicates that under the experimental conditions, membrane filtration is controlled by concentration polarisation. A feed concentration of 0.05 g/L showed a final membrane efficiency of 53% (Final flux = 256 L/m^2 h (J_F), Initial Flux = 477.3 L/m^2 h (J_i), PWF = 440.7 L/m^2 h at 1 bar) as opposed to the higher final membrane efficiency observed at the lowest feed concentration of 0.03 g/L at 72% (Final flux = 367.1 L/m^2 h (J_F), Initial Flux = 508.1 L/m^2 h (J_i), PWF = 454.7 L/m^2 h). The degree of flux sustainability is also apparent, with the highest trend being observed at the lowest feed concentration. It can be seen from Fig. 5b that after ten minutes of filtration at constant pressure, there was a loss in membrane efficiency for 0.1 g/L by 45%, 0.05 g/L by 39% and 0.03 g/L by 25%. After the ten minute mark, 0.03 g/L showed stable flux sustainability since only a 3% reduction in membrane efficiency was realised compared with more reduction of 14% and 8% in membrane efficiency for flux of 0.1 g/L and 0.05 g/L respectively.

Temperature Effects

The variation in feed temperature within the range of 35–45°C on flux sustainability and membrane efficiency has been investigated during the microfiltration of bentonite suspensions. Temperature can also affect the surface potential of the particles, since temperature can readily displace the equilibrium between the ionized groups and the medium. For bentonite suspensions, similar temperature dependence to other electrostatically stabilized systems could be expected. However, the flat geometry, the layer structure and the different origin of the charges on the faces and edges of the clay platelets confer particular characteristics to bentonite that might have a decisive effect on the involved interaction forces.

Figures 6a–c shows that there is a slight advantage to using higher feed temperatures in terms of membrane efficiency and flux sustainability. Increasing the feed suspension temperature increases the initial permeate flux and also throughout the experiment. Membrane flux sustainability is shown to increase with increasing temperature from 35°C to 45°C. In all cases, concentration polarization establishes itself and the permeate flux decreases progressively. At the lowest temperature of 35°C, a final membrane efficiency of 44% (Final flux = 210.9 L/m^2 h (J_F), Initial flux = 471.2 L/m^2 h (J_i), PWF = 454.7 L/m^2 h at 1 bar) was realised. As the temperature increased to 40°C, the flux sustainability improved by 5%, with a final membrane efficiency increasing to 50% (Final flux = 265.4 L/m^2 h (J_F), Initial Flux = 530.2 L/m^2 h (J_i), PWF = 415.1 L/m^2 h at 1 bar) and with the highest temperature investigated at 45°C, the flux sustainability was the highest attained with a higher final efficiency at 55% (Final

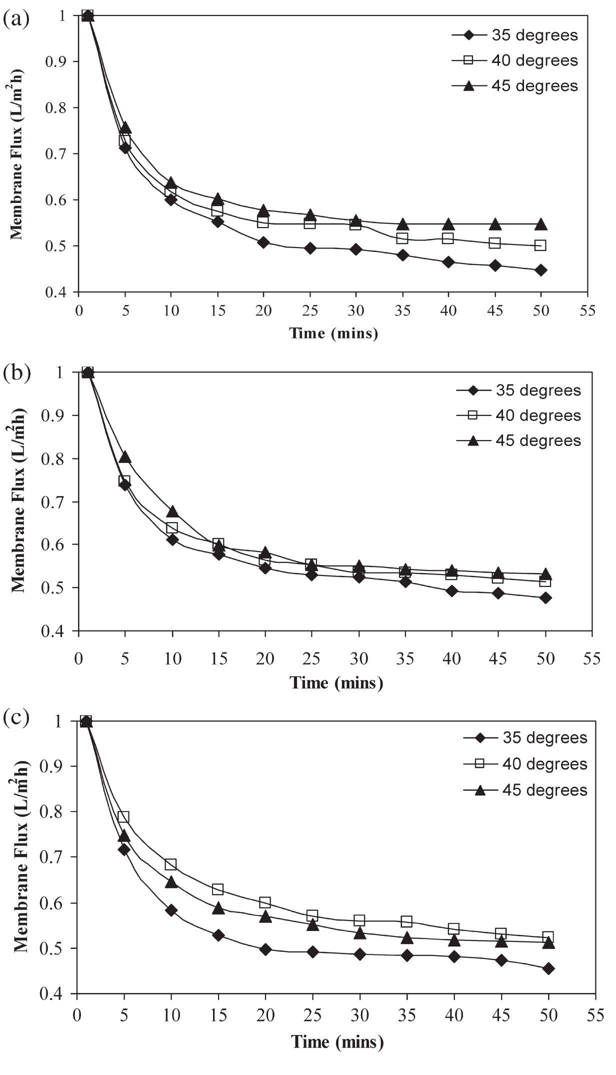

Figure 6. Temperature effects on flux sustainability at a) 2.5 L/min, b) 1.8 L/min, c) 1.2 L/min.

Flux = 318.1 L/m^2 h (J_F), Initial Flux = 581.2 L/m^2 h (J_i), PWF = 447.6 L/m^2 h at 1 bar). The flux is increased with increased temperature of the suspension because the viscosity of the suspension is reduced at higher temperatures, hence there is more permeate realised through the membrane pores. The same trend is witnessed at lower flowrates of 1.8 L/min and 1.2 L/min.

The viscosity in a liquid suspension is the ratio of the shearing stress to the velocity gradient. In general, the viscosity of a simple solution decreases with increasing temperature and vice versa. As temperature increases, the average speeds of the molecules in a liquid increase. Also, with respect to a bentonite suspension, the particles spend less time in contact with each other; hence, there is less agglomeration within the suspension. As the temperature is increased, the thermal or kinetic energy of the water and bentonite molecules increase and become more mobile. There is also some molecular interchange due to the molecules moving faster but there are additional substantial attractive, cohesive forces between the molecules in the bentonite suspension. Their average intermolecular forces also decrease and the suspension particles gain more kinetic energy. Particle cohesion and interchange contribute to the overall viscosity. Increasing the temperature of the feed suspension reduces the cohesive forces while simultaneously increasing the rate of molecular interchange. The former factor tends to cause a decrease in shear stress while the latter causes it to increase. The net result is that suspensions show a reduction in viscosity with increasing temperature.

Effects of Turbulence Promoters

The figures below clearly show that for all the runs with the different turbulence promoters, the flux sustainability is always higher than the run without the promoters. This shows that the use of promoters reduces the membrane fouling and increases membrane efficiency over time. It can be seen from Figs. 7 to 9 that there is a considerable improvement in membrane flux sustainability for all the cases studied. The improvement in permeate flux, defined as the relative flux improvement obtained by using the static turbulence promoter compared to the flux without using the promoter is shown in Figs. 7–9.

Pressure Effects

Figure 7 shows the variations of the permeate flux with operation time obtained with the use of three turbulence promoters (TP) and without a promoter (NTP mode) for the ceramic microfiltration membrane. The experiments were carried out at 2 L/min, 1.5 L/min and 1.2 L/min at various system pressures from 1 bar to 2.5 bar. The increase in the flux improvement reached a maximum of up to 45% through the experiment. For the NTP mode, the observed change in flux with time indicates severe particle deposition on the membrane surface, thus limiting flux. After a rapid decline during the first few minutes of filtration, there appears to be a levelling off after about half an hour. The flux sustainability is low in this case. However, the use of the turbulence promoters at all flowrates caused a large improvement of the permeate fluxes. Figure 7a shows that at a high flowrate of 2 L/min and a low system pressure of 1 bar, there was a very significant increase in flux sustainability

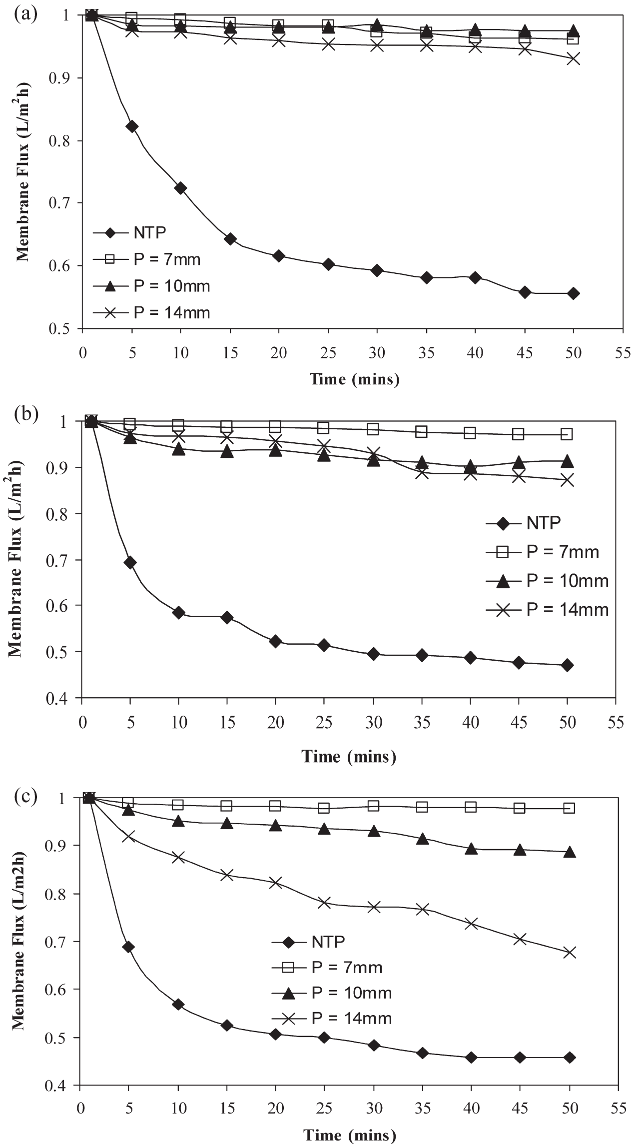

Figure 7. Effects of promoters at 2 L/min at a) 1 bar, b) 2 bar and c) 2.5 bar.

for all the promoters studied and membrane efficiency increased considerably compared to the membrane with no turbulence promoter (NTP). The promoter of pitch length = 14 mm TP_{14} showed the lowest membrane flux sustainability values with a final membrane efficiency of 93% (Initial Flux = 240 $L/m^2 h$ (J_i); Final flux = 223.2 $L/m^2 h$ (J_F), PWF = 311.35 L/

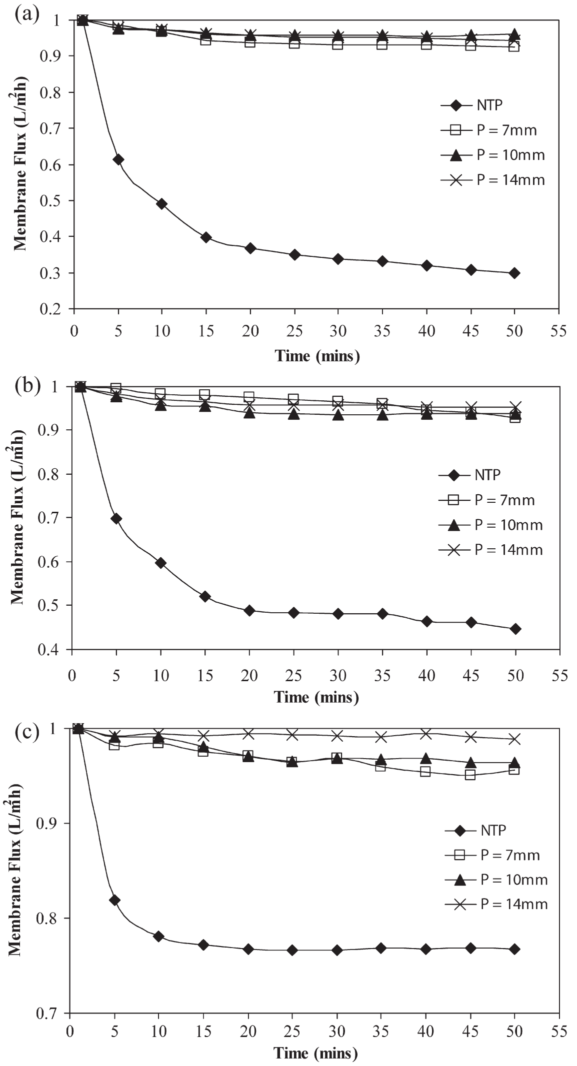

Figure 8. Effects of promoters at 2.5 L/min at a) 0.1 g/L, b) 0.05 g/L and c) 0.03 g/L.

m^2 h at 1 bar). This is still very much higher than the final efficiency of the empty membrane at 55% (Initial flux = 285.4 L/m^2 h (J_i); Final flux = 158.7 L/m^2 h (J_F), PWF = 337 L/m^2 h at 1 bar), which is 38% lower. The promoter with a pitch length of 10 mm TP_{10} showed the highest final membrane efficiency with a value of 97% (Initial Flux = 257.4 L/m^2 h (J_i), Final flux = 249.7 L/m^2 h (J_F), PWF = 311.35 L/m^2 h at 1 bar) whilst the pitch length = 7 mm TP_7 showed a value of 96% (Initial Flux = 265.4 L/m^2 h (J_i); Final flux = 254 L/m^2 h (J_F), PWF = 311.35 L/m^2 h at 1 bar).

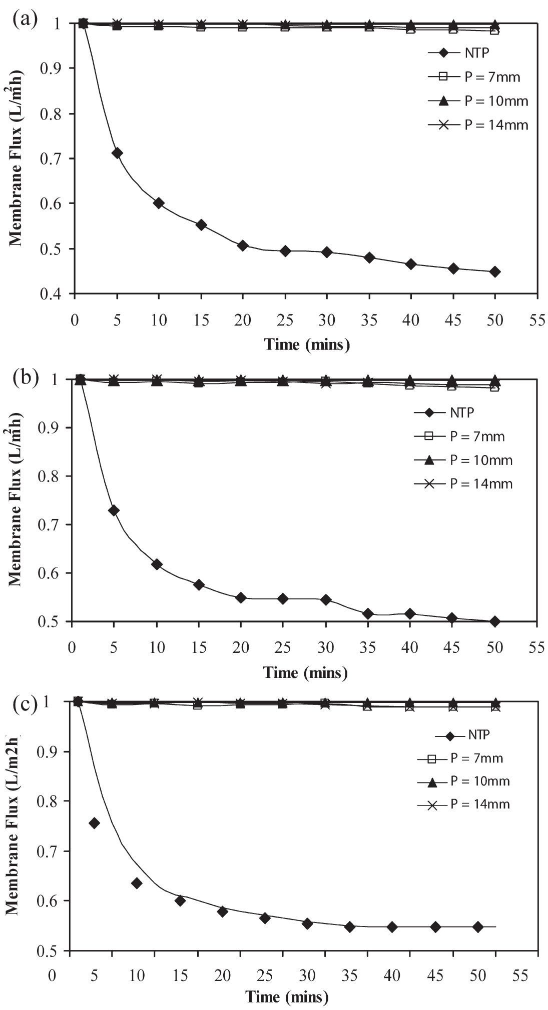

Figure 9. Effects of promoters at 2.5 L/min at a) 35°C, b) 40°C, and c) 45°C.

This is indicative of very good flux sustainability at low pressures with turbulence promotion. At the mid-point of the experiment, there was already a high foulant deposition indicated by a low flux sustainability and high membrane efficiency loss with performance at 60% as seen for the empty membrane in Fig. 7. The three promoters used maintained a high flux sustainability and efficiency values at the mid-point of the experiments were 95%, 98% and 98% for pitch lengths = 14 mm TP_{14} and 10 mm TP_{10}, 7 mm TP_7. Overall, it can be seen that there was a loss in membrane efficiency of 45% using the empty membrane but a loss of 3%, 4%, and 7% respectively using the turbulence promoters pitch length 7 mm, 10 mm, and 14 mm. The sustainability of flux within the empty membrane was considerably lower than that experienced at 1 bar and showed a lower final membrane efficiency of 47% (Initial flux = 459.4 L/m^2 h (J_i), Final flux = 216.1 L/m^2 h (J_F)). This can be attributed to a higher rate of deposition of particles on the membrane surface at higher pressures. Once again, there was very high flux sustainability experienced for the three turbulence promoters, which indicate a lower deposition rate of bentonite particles on the membrane surface due to the effect of turbulence generation. It can be seen from Fig. 7 that final membrane efficiency values for the three promoters Pitch length = 14 mm TP_{14}, 10 mm TP_{10}, and 7 mm TP_7 are 87%, 91%, and 97% respectively. These figures also suggest that the promoter with the tightest pitch (7 mm) proved the most effective in maintaining high flux sustainability under these conditions. It can also be concluded from Fig. 8 that there was a 53% loss in efficiency at the end of the experiment using the empty membrane compared with 3%, 9%, and 13% respectively using the turbulence promoters pitch length 7 mm TP_7, 10 mm TP_{10}, and 14 mm TP_{14}. The mechanism of turbulence generation has been covered extensively in (12) whilst working with turbulence promoters and yeast suspensions.

At the highest system pressure studied, the flux sustainability for the empty membrane was lower than at 1 and 2 bar and membrane efficiency had a final value of 45% (Initial flux = 522 L/m^2 h (J_i); Final flux = 239.4 L/m^2 h (J_F)). The filtration with the three promoters showed much higher membrane efficiency values than the empty membrane as detailed in Fig. 7. Final membrane efficiencies were 67% (Initial flux = 662.4 L/m^2 h, Final flux = 448.4 L/m^2 h, PWF = 301.52 L/m^2 h at 1 bar), 88% (624.5 L/m^2 h, Final flux = 553.8 L/m^2 h, PWF = 318.27 L/m^2 h at 1 bar) and 97% (Initial flux = 459.6 L/m^2 h, Final flux = 449.1 L/m^2 h, PWF = 311.35 L/m^2 h at 1 bar) for promoters of pitch length = 14 mm TP_{14}, 10 mm TP_{10}, and 7 mm TP_7. Once again, a similar trend was established with pitch length = 14 mm showing the least improvement and pitch length = 7 mm showing the greatest improvement. Over the fifty minute duration of filtration, the empty membrane mode of operation showed a loss in 55% in operational efficiency, while the promoters exhibited 33%, 12% and 3% loss in operational efficiency. Similar behavior was noticed for the curves at 1.5 L/min and 1.2 L/min.

Feed Concentration Effects

Crossflow microfiltration results in Figs. 8a–c indicate that the main factor limiting the permeation flux is the formation of a polarization and fouling layer on the surface of the membrane. From the curves without turbulence promoters (NTP), fouling occurred during the first few minutes and this initial flux decline is usually attributed to concentration polarization and the rapid formation of the fouling deposit, in this case, bentonite.

Figures 8a–c compare the fluxes obtained from the ceramic membrane during the filtration of different feed concentrations at 2.5 L/min. It can be seen from Fig. 8 that the three different promoters greatly improved flux sustainability with final efficiencies in the range of 93% to 96% for the filtration of a 0.1 g/L suspension. This is in extreme contrast to the final membrane efficiency of the empty membrane at the same conditions. The empty membrane showed a final membrane efficiency of 30% (Initial flux = 554.8 L/m^2 h, Final flux = 166.1 L/m^2 h, PWF = 774.17 L/m^2 h at 1 bar), indicating an overall loss of 70% with time. This is indicative of the severe fouling potential of the suspension used. The promoters, however, showed similar behavior in terms of membrane flux sustainability, with total losses in efficiency within a range of 4–7%. Similar behavior was realized with the filtration of a 0.05 g/L bentonite suspension at 2.5 L/min. There was a significant enhancement of membrane efficiency, with final values for the promoters in the range of 93% to 95%. The filtration with the empty membrane showed poor flux sustainability with a rapid decline over time. After 15 minutes, there was a loss of 48% in efficiency and a further loss of 55% efficiency by the end of the experiment. Figure 8 shows the pattern of flux sustainability curves during the filtration of a 0.03 g/L suspension at 2.5 L/min. It can be seen that similar trends to those for 1.8 L/min and 1.2 L/min emerge, with final efficiency values in a range between 95% and 98%. The promoter with the widest pitch proved slightly the most effective in this case with a loss of 2% over the filtration period.

Temperature Effects

Figures 9a–c shows the effects of using turbulence promoters on membrane flux sustainability at higher feed temperatures. The curves from the graphs show that there was very high flux sustainability for all the temperatures studied and there were similar trends at all the studied flowrates. The enhanced scouring of the membrane surface is enhanced by helical flow pattern created by the helical threads of the turbulence promoters. In addition to the helical flow pattern, which establishes rotational, or swirling secondary flows, the periodic alternation of the flow establishes the generation of vortices which further increase the shear rate in the neighbourhood of the membrane surface. It subsequently reduces the thickness of the bentonite cake that has accumulated on the membrane surface. The increased membrane performance at higher feed temperatures can be attributed to the thinning of the suspensions, decrease in the viscosity of the suspensions, and an increase in the kinetic energy of the bentonite suspension. It can be seen from Fig. 9 that all the turbulence promoters show very great flux sustainability over the duration of the experiments.

CONCLUSIONS

The investigation of the microfiltration of bentonite suspensions showed that under various operating conditions, there was progressive flux decline over time and steep reductions in flux sustainability for increased pressure and feed concentrations. Increasing the feed temperature however showed higher flux sustainability and improved performance of the membrane.

The experimental results clearly show improved membrane efficiency and flux sustainability during crossflow microfiltration via turbulence promoters of varying pitch lengths. It can also be concluded from the data generated for pressure effects that the promoters with the tightest pitch length (TP_{7mm}) showed the highest flux sustainability at all flowrates and pressures studied. On the other hand, the promoter with the widest pitch length (TP_{14mm}) proved the least effective in enhancing membrane efficiency although it showed considerably higher flux sustainability than the empty membrane. However, for feed concentration and feed temperature effects, the promoters showed almost identical behavior with high flux sustainability and also high membrane performance when using the promoters. However, the promoter TP_{14mm} showed slightly higher membrane performance. This study has shown that the use of static turbulence promoters with tubular ceramic membranes of small length can provide a significant improvement of crossflow microfiltration of bentonite suspensions with a possibility to carry out the process at low crossflow velocities. In the experiments reported, both the retentate and the permeate streams were returned to the feed tank. Furthermore, with the use of turbulence promoters within the tubular membranes, the improvement of membrane cleaning was observed and it was possible to recover the initial membrane permeability without much difficulty.

SYMBOLS AND ABBREVIATIONS

TP	Turbulence promoter
NTP	No turbulence promoter
TP_7	Pitch length = 7 mm
TP_{10}	Pitch length = 10 mm
TP_{14}	Pitch length = 14 mm
J_V	Flux value
J_i	Initial flux value
J_F	Final flux

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