Reduction of membrane fouling using a helical baffle for cross flow microfiltration

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Abstract

The introduction of turbulence promoters such as helical baffles were shown to enhance permeate flux during crossflow microfiltration. Helical inserts reduce hold-up in the feed channel; increase fluid velocity and wall shear rates and produce secondary flows or instabilities. The aim of this work was to investigate the influence of helical baffles on permeate flux during the microfiltration of titanium dioxide (TiO_2) dispersions and bakers yeast solutions. Tubular, single channel ceramic membranes with nominal pore size of 0.2μm were used. Variations of the helical baffle geometries, which are the number of turns per baffle length, were investigated. It is found that the insertion of helical baffles increased the permeate flux. In some cases, the increase was more than 100%. The effect of number of turns per baffle length shows that the permeate flux increases with the number of turns but decreases when the number of turns is more than 4 turns per 50 mm baffle length. Thus, the optimum number of turn is 4 turns per 50mm.

***Keywords**:* helical baffles, turbulence promoters, microfiltration, TiO_2, bakers yeast

1. Introduction

Over the last two decades, the use of membrane filtration technologies in separation processes has proliferated. Crossflow microfiltration is a pressure-driven process that is widely used in purifying, concentrating or separating macromolecules, colloids and suspended particles from solution[1]. Recently, ceramic membranes have found wide range of applications in the areas of food, chemical, biochemical, energy and environmental engineering because of their outstanding heat resistance, solvent endurance and resistance to acid and alkali[2]. However, enhancing the permeate flux still remains a topical obstacle that limits the industrial development of the membrane filtration processes. The accumulation of materials near the membrane-liquid surface, known as fouling, results in permeate flux decline. Membrane fouling is the major problem and the bottleneck for membrane separation technology. Membrane fouling is due to concentration polarization, specific adsorption, gel layer formation and membrane pore plugging[3].

The various modes of pore blocking are a function of the solid/solute size and shape in relation to the membrane pore size distribution[4]. The complete pore-blocking phenomenon occurs when the pore entrance is sealed by the micro particles. For the similar analogy, pore bridging is caused by the partial obstruction of particles of the entrance. However, if material not rejected by the pore entrance is adsorbed or trapped on the pore wall or in the membrane support, it is known to be internal pore blinding. Over the years, a number of measures have been introduced that are aimed at eliminating or reducing membrane fouling. These include applying electrophoretic and electroosmosis effect by using an electric field[5-7], Transmembrane Pressure Pulsing (TPP) by frequently and periodically reversing the transmembrane pressure[8], rapid backpulsing and backflushing [9-12], membrane surface modification[13-15], gas sparging [16-17] and many others.

Another technique of controlling these flux-limiting phenomena are by using hydrodynamic approaches such as creating unsteady flows by pulsations using collapsible-tube pulsation generator[18], slug flow[19], and the use of dynamic membranes[20]. The use of turbulence promoters or inserts in the tubular membrane is another reported technique of applying hydrodynamic methods. These turbulence promoters or inserts come in many shapes and sizes. There are static rods, metal grills, cone shape inserts, spiral wire, disc and doughnut shape inserts. There is also turbulence promoters made from rods with intermittent spaced rings cemented on them. These rings can also be replaced with other shapes such as square cross section rings. These inserts can be collectively called as baffles.

Helical baffles reduce membrane fouling by producing a helical flow pattern and generating secondary flow to combat the formation of a concentrated particle layer immediately above the membrane surface. The helical flow is that which flows along the helical groove of the helical baffles. These helical vortices create fluid instabilities in the feed and thus mechanically scarp the surface of the membrane. Also, helical baffles are expected to perform better than rod inserts implying that the helical vortices improve the mixing between the boundary layer on the membrane and the bulk fluid to a greater extent than occurs by simply generating turbulent flow using cylindrical inserts. A detailed study of the performance of helical screw-thread inserts in tubular membranes was carried out[21]. They noted that the screw-thread design generates Dean vortices which promotes good mixing of the fluids and minimizes concentration polarization effects. They found that helical inserts produced much higher fluxes at low crossflow rates than membranes without inserts (up to a factor higher than 6).

An experimental study to evaluate flux performance and solids retention efficiency of a ceramic membrane system in the microfiltration (MF) of a primary municipal sewage effluent by employing a helically wound baffle installed inside the cross flow channel also has been investigated[22]. The membrane used are ceramic membranes (Fairey Ind, UK) with nominal pore diameters $D = 0.22, 0.35, 1.3$ μm and 12 star-shaped flow channels. The baffles were helically wound and soldered onto a 0.25 mm central wire. They reported that by installing the helical baffle inserts inside the flow channel, a 22% flux improvement was achieved.

The use of helical baffles in the membrane filtration of bakers yeast and dodecane-water emulsion was experimented[23]. A mineral membrane (Carbosep, France) was used. Helical baffles of different number of turns (1,2,4,6) per 25 mm baffle length were made by winding a steel wire (1 mm diameter) on steel rod of 3.1

or 2.3 mm diameter. They reported that under the operating conditions, the use of a helically wound baffle in a membrane managed to increase the permeate flux, in some cases up to more than 50% at the same hydraulic dissipated power and without any additional equipment such as pulsating pump or any backwashing system. The use of a helical baffle inserted in a mineral membrane for the clarification of a highly charged red wine has also been carried out[24]. It is reported that the use of helical baffles, under the hydrodynamic conditions, increased the permeate flux rate from 10 $L/m^2.h$ to 25 $L/m^2.h$. Furthermore, an increase of about 200% of flux was possible even with the same hydraulic dissipated power.

An experiment using a tubular membrane system fitted geometrical inserts of disc shape and doughnut to create a periodically grooved channel was carried out[25]. They investigated membrane performance for these systems alone and with the combination of pulsed flow for the ultrafiltration of 10 to 25 g/L solution of the purified whey protein Bipro using tubular membrane. The results were then compared with a conventional system operating under the conditions of crossflow velocity and transmembrane pressure. With the incorporation of these baffles, the filtration performance improved by a factor of about 2.5. Further improvement was noticed when pulsed flow was used.

Objectives of this study was to investigate the effects of using different geometries of baffles, which is the number of turns per baffle length, on the permeate flux for the microfiltration of titanium dioxide (TiO_2) dispersions and bakers yeast solutions. Experiments were conducted using the different geometries of baffles fabricated for TiO_2 dispersions and bakers yeast solutions. Also, the effect of baffles and the behaviour of permeate flux on feeds that differ in nature: TiO_2 dispersions (inorganic) and bakers yeast solutions (biological) was analyzed. At the present time, most researches have investigated the effects of using baffles using membranes with smaller inner diameters from 6mm to 12mm and membrane lengths from 250 to 400mm. The current research uses membrane with an internal diameter of 14 mm and membrane length of 600mm.

2. Materials and methods

A laboratory scale membrane filtration rig was fabricated, which consisted of a feed tank, a feed pump, a filtration unit, valves and measuring equipment such as flow meter, pressure gauges and an electronic balance as shown in Figure 1. A tubular, single circular shape channel ceramic membrane purchased from Fairey Industrial Ceramics Limited, England measuring 14 mm inner diameter and 600 mm long with a membrane surface area of $0.06m^2$ was used. The membrane was made of alumina with an average pore size of 0.2μm. The properties of the ceramic membrane as given by the manufacturer are given in Table 1. The ceramic membranes substrate and membrane layer are insensitive to bacterial action, corrosion and abrasion resistant and can be operated at high temperatures and pressure thus making it possible for repeated membrane regeneration after fouling.

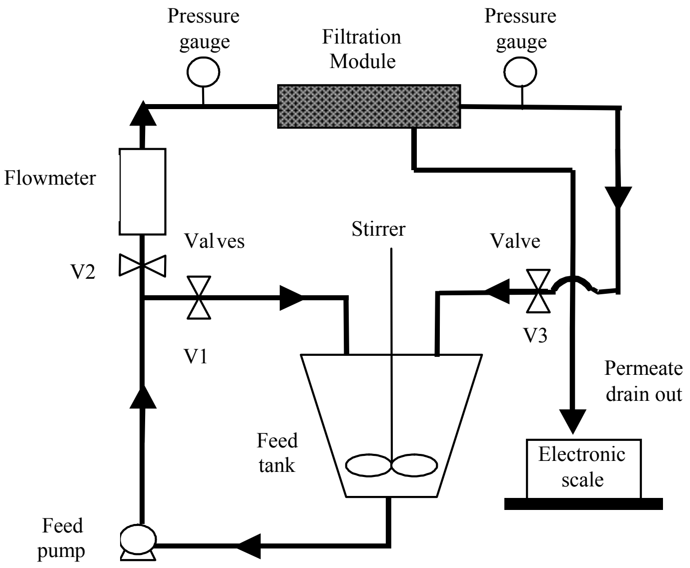


FIGURE.1 : Schematic Diagram of the Flow of the Microfiltration Process

Table 1
Properties of the ceramic membrane

Material	δ-alumina
Maximum pore size (μm)	5
Average pore size (μm)	3
Porosity (Vol %)	35
Flexural Strength (MPa)	45
Diameter (mm)	20
Length (mm)	600
Channel : Circular OD (mm) Circular OD (mm) Star OD (mm) Star ID (mm)	20 14 14 maximum
Filtration area (m^2)	0.06
pH range	0.5-13.5
Maximum Temperature (°C)	140
Maximum Pressure (bar)	8

Helical baffles of different number of turns such as 1,2,4,6 per 50 mm baffle length were fabricated using stainless steel. These helical baffles were made by winding and soldering a stainless steel wire of 3 mm diameter on stainless steel rod of 6 mm diameter. There is a gap of about 1 mm between the membrane inner surface and the baffle height. A rod baffle measuring 12 mm diameter, which represents a helical baffle with an infinite number of turns, was also made. A new specially designed baffle-double helix in shape measuring 12 mm in diameter was fabricated. These baffles were centrally supported inside the membrane by placing the ends of the baffle rod in the special custom-made support found in the housing of the membrane module. Figure 2 shows the schematic diagram of a helical baffle inserted in a tubular membrane whereas Figure 3 shows the photographic view of the different geometries of helical baffles.

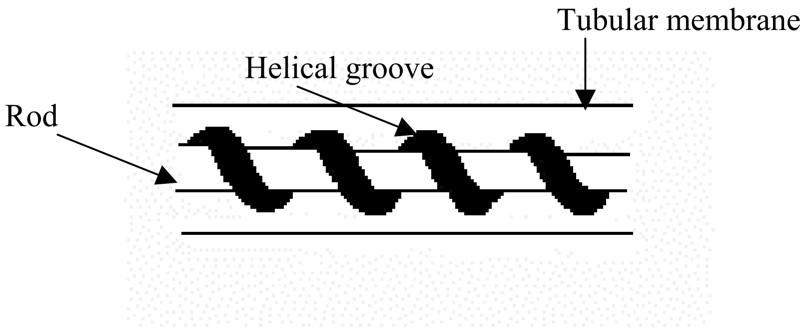


Fig.2. Schematic diagram of a helical baffle inserted in a tubular membrane

The titanium dioxide used was the technical grade TR 92. The concentration of TiO_2 was 1 g/L and was prepared by adding 40g of titanium dioxide with 40L of distilled water. The baker's yeast (Saccharomyces cerevisiae) used was purchased from Mauri Fermentation (M) Sdn Bhd. as compressed yeast. The concentration of the bakers yeast was also 1g/L. The solution in feed tank was continuously recirculated to get a better mixing and dispersion with the help of a stirrer. Particle size distribution (PSD) measurements were done by using Malvern Laser Diffraction Instrument (Malvern Mastersizer E). The ceramic membranes were cleaned after each experiment in order to restore the membranes pure water flux to a minimum of at least 95% of the original value. The regeneration of the fouled ceramic membranes was done with an effective and fast membrane cleaning method. This consisted of a combined simultaneous caustic cleaning and oxidation procedure carried out at $80^{O}C$ using 1% w/w NaOH solution with the addition of 5g/l of H_2O_2 as the oxidizing agent. Residual fouling formed by strong surface adsorption is attacked while tenacious surface deposits are rapidly broken down with this formula. The integrity of the ceramic membrane was not affected even though this cleaning method was very powerful.

a. 1 turn per 50 mm

d. 6 turn per 50 mm

b. 2 turn per 50 mm

e. Double Helix

c. 4 turn per 50 mm

f. Rod baffle

FIGURE 3 : Photographic View of Different Geometries of Helical Baffles.

The Transmembrane pressure was constant at 20 psi for all the experiments. Experiments were then conducted using the different turns of baffles fabricated *i.e.* 1,2,4,6 per 50 mm baffle length. Each experiment was run for two hours. The permeate was collected every five minutes for the first hour and ten minutes for the subsequent hour and weight of the permeate was measured by using an electronic balance. The permeate flux was constantly returned to the feed tank as with the retentate in order to maintain a constant inlet feed concentration. Each set of experiment is repeated five times and the average value is taken in order to have a reproducible and repeatable data.

The different membrane resistance for the membrane could be calculated by using the following equation:

$$\text{Average flux, } J = \frac{\Delta p}{\mu(R_m + R_c)} \tag{1}$$

Where J is the average flux (L/m^2.hr), Δp is Transmembrane pressure (psi), μ is the viscosity of the feed (Pa.s), R_m is the clean membrane resistance (m^{-1}) and R_c is the membrane resistance due to gels, cake and adsorption (fouling) (m^{-1}).

Rewriting equation 1 gives,

$$\frac{J}{\Delta p} = \frac{1}{\mu(R_m + R_c)} \tag{2}$$

From equation 1, the slope of a plot J versus Δp gives the value for $\frac{1}{\mu(R_m + R_c)}$

The value for the clean membrane resistance R_m could be found from the following equation:

$$\text{Average flux for clean membrane, } J_m = \frac{\Delta p}{\mu R_m} \tag{3}$$

where J_m is the average flux for clean membrane (L/m^2.hr), Δp is Transmembrane pressure (psi), μ is the viscosity of the feed (Pa.s), R_m is the clean membrane resistance (m^{-1}).

Rewriting equation 3,

$$\frac{J_m}{\Delta p} = \frac{1}{\mu R_m} \tag{4}$$

From equation 3, the slope of a plot J_m versus Δp gives the value for $\frac{1}{\mu R_m}$. With the value of μ known and assumed to be that of water (because the feed solution is very dilute), the value of R_m could be as well as the value of R_c when each of the baffles is used.

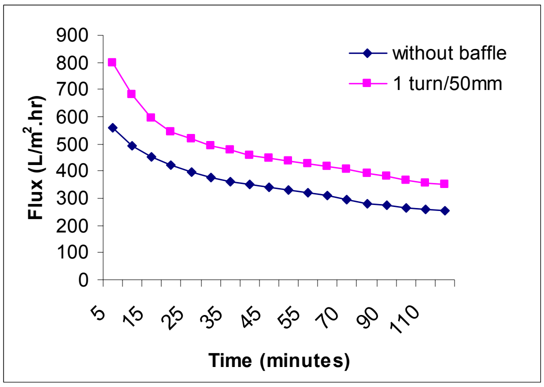
3. Result and discussion

The average particle size for TiO_2 was found to be 0.58 μm and for bakers yeast was 1.56 μm. Thus, the average size of the particle in feed stream is bigger than the average pore size of the ceramic membrane, which is 0.2 μm. As such, theoretically the entire feed particle 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. Most fouling is due to the filter cake formation on the surface of the membrane.

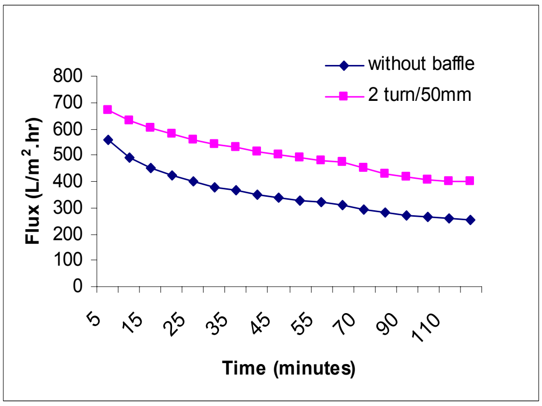
Table 2 shows the results of average flux and the percentage increase of average flux in comparison to the run without baffles for the microfiltration of 1 g/L of TiO_2 at 20 psi TMP. It clearly shows that the 4 turns per 50 mm helical gives the highest average flux at 520.8 L/ m^2.hr, an increase of 104.9% compared to the run without any baffles with produces an average flux of 520.8 L/m^2.hr. The 2 turns per 50 mm gives the second highest average flux with an increase of around 55.8% followed by the double-helix baffle (44.7%), 1 turns per 50 mm (36.6%), 6 turns per 50 mm (27.8%) and finally the rod baffle (10.9%). Figure 4 clearly shows that for all runs with the baffle, the flux is always higher than the run without any baffles. This proves that the presence of baffle reduces membrane fouling thus increases the flux.

Table 2
Average flux and percentage increase of average flux at different types of baffles for the microfiltration of 1 g/L TiO_2 at 20 psi TMP.

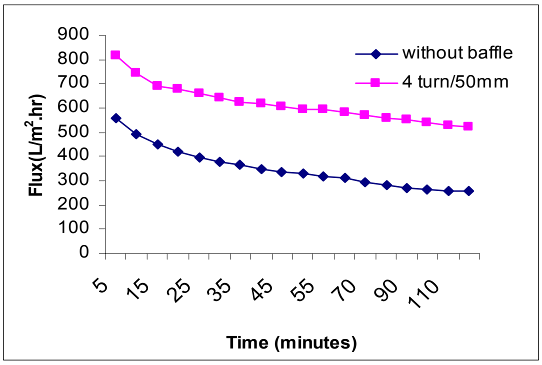
Types of Baffles	Average Flux (L/m^2.hr)	Percentage increase compared to run without baffles
4 turns/50 mm	520.8	104.9%
2 turns/50 mm	398.0	55.8%
Double helix	369.5	44.7%
1 turn/50 mm	349.0	36.6%
6 turns/50 mm	326.3	27.8%
Rod baffle	283.3	10.9%
Without baffle	255.4	0



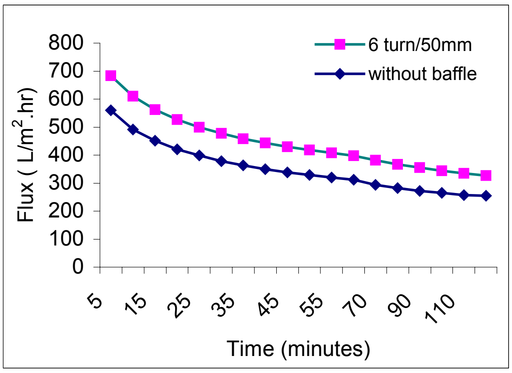
a) 1 turn/50 mm



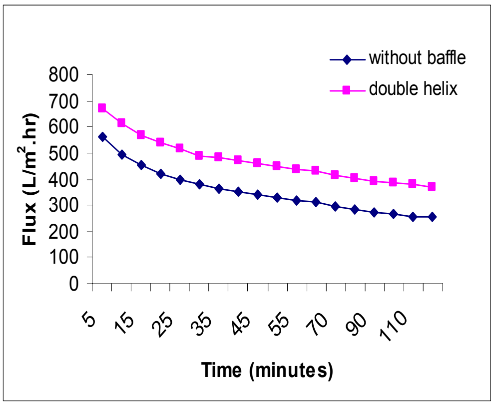
b) 2 turn/50 mm



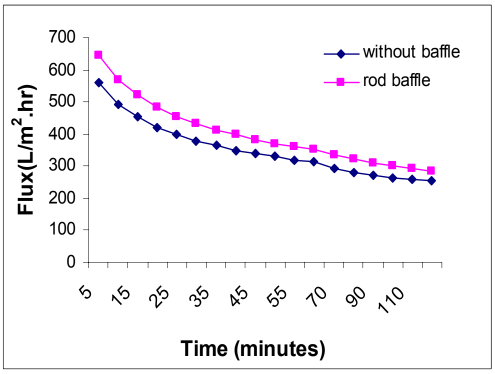
c) 4 turn/50 mm



d) 6 turn/50 mm



e) Double Helix



f) Rod Baffle

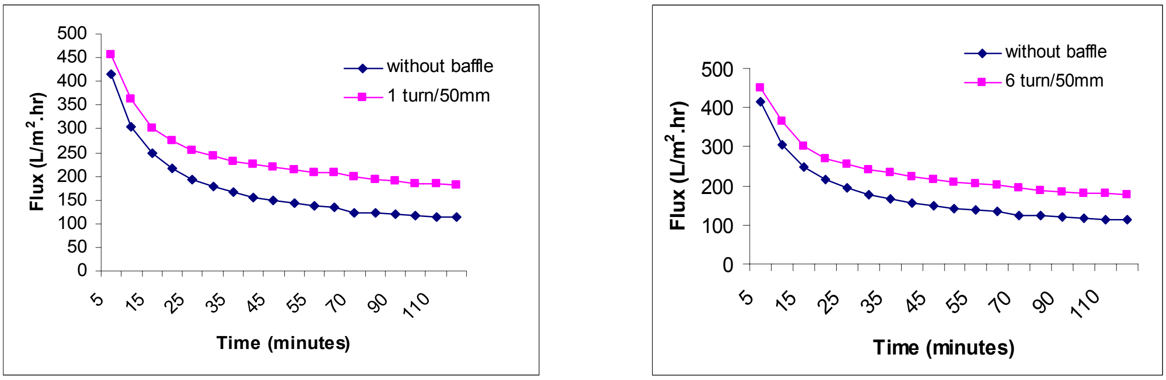
FIGURE 4 : Flux Performance of Different Types of Baffles for 1g/L TiO_2 at 20 psi TMP

Meanwhile, Table 3 shows the results of average flux and the percentage increase of average flux in comparison to the run without baffles for the microfiltration of 1 g/L of bakers yeast at 20 psi TMP. As in the case with TiO_2, it clearly shows that the 4 turns per 50 mm helical gives the highest average flux at 214.6 L/m^2.hr, an increase of 88.2% compared to the run without any baffles will produce an aver age flux of 114.0 L/m^2.hr. The 2 turns per 50 mm gives the second highest average flux with an increase of around 87.9% followed by the double-helix baffle (61.5%), 1 turns per 50 mm (58.7%), 6 turns per 50 mm (55.9%) and finally the rod baffle (52.9%). Figure 5 clearly shows that the average flux for the run with bakers yeast is always higher with the presence of baffles. Similarly for the microfiltration TiO_2, this also proves that the presence of baffle reduces membrane fouling thus increases the flux

Table 3
Average flux and percentage increase of average flux at different types of baffles for the microfiltration of 1 g/L bakers yeast at 20 psi TMP.

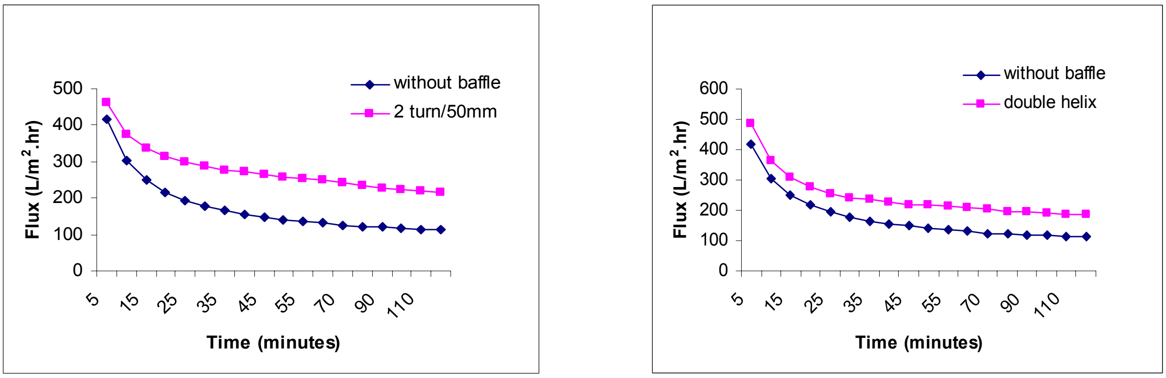
Types of Baffles	Average Flux (L/m^2.hr)	Percentage increase compared to run without baffles
4 turns/50 mm	214.6	88.2%
2 turns/50 mm	214.2	87.9%
Double helix	184.1	61.5%
1 turn/50 mm	180.9	58.7%
6 turns/50 mm	177.7	55.9%
Rod baffle	174.3	52.9%
Without baffle	114.0	0

When a helical baffle is inserted in the tubular membrane, the flow increases at the membrane surface. The flow of the feed fluid becomes constricted and the area of flow also decreases. Thus, the when the surface area decreases, the average fluid velocity becomes higher. The feed flows faster and the wall shear rate near the membrane wall increases. Rapid flow at a membrane surface will reduce the effects of concentration polarization in membrane systems[26]. This will eventually reduce the formation of filter cake on the surface of the membrane. The insertion of a helical baffle changed the flow field. There probably exists a major rotational component and the particle deposition rate on the membrane surface decreased with the presence of helical baffles[24]. This rotational component creates turbulence that scours the surface of the membrane. The flow field generated by the helical baffle probably scours the surface of the membrane more than in the case without the baffle. This scouring action directly removes the deposited particles from the surface of the membrane thus increasing the mass transfer away from the surface and reducing surface concentration. When the surface concentration is reduced, the permeate easily penetrates the membrane. This is probably the reason for the increase in permeate flux for the TiO_2 dispersions and bakers yeast solutions.



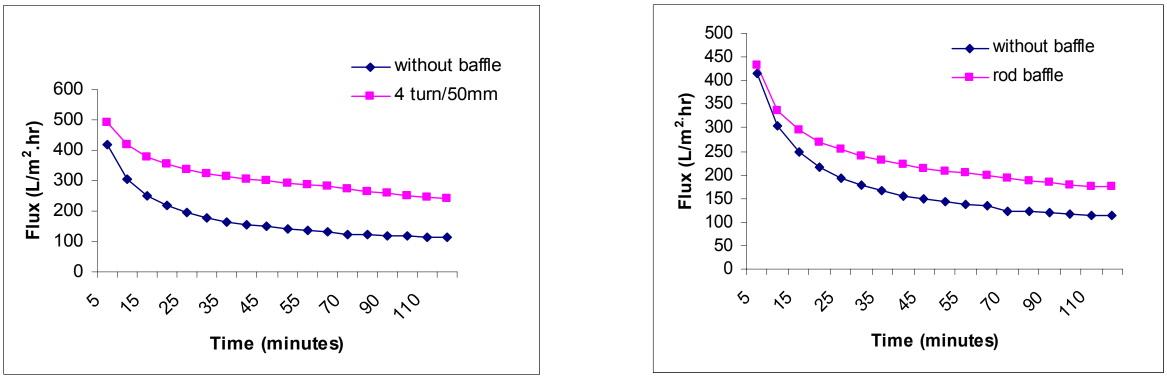
a) 1 turn/50 mm

d) 6 turn/50 mm



b) 2 turn/50 mm

e) Double Helix



c) 4 turn/50 mm

f) Rod Baffle

FIGURE 5 : Flux Performance of Different Types of Baffles for 1g/L Bakers Yeast at 20 psi TMP

There are an optimal number of turns per baffle length that can be determined experimentally for obtaining the maximum flux[23]. In this research, it is noted that if the number of turns for the helical baffle is increased from 1 turn per 50 mm to 4 turns per 50 mm, the average flux increases. But when the number of turns is further increased to 6 turns/50 mm baffle and infinite number of turns (represented by the rod baffle), the permeate flux decreases. This is shown in Figure 6. The data used here are taken form the microfiltration of 1 g/L TiO_2 at 20 psi TMP.

The rod baffle exhibits a lower permeate flux probably due to the fact that it does not generate turbulence and thus does not have the scouring effects as compared to helical baffles. Based on Figure 6, it is observed that the number of turns decreases when the number of turns is more than 4 turns per 50 mm. Hence, we can conclude that a helical baffle made up of 4 turns per 50 mm baffle length is optimum. These results are in excellent agreement with those obtained by Gupta *et al.* Even though the baffles used by them and this research are in different geometry, but the results obtained by them and this research shows that there is a baffle that gives the optimum flux.

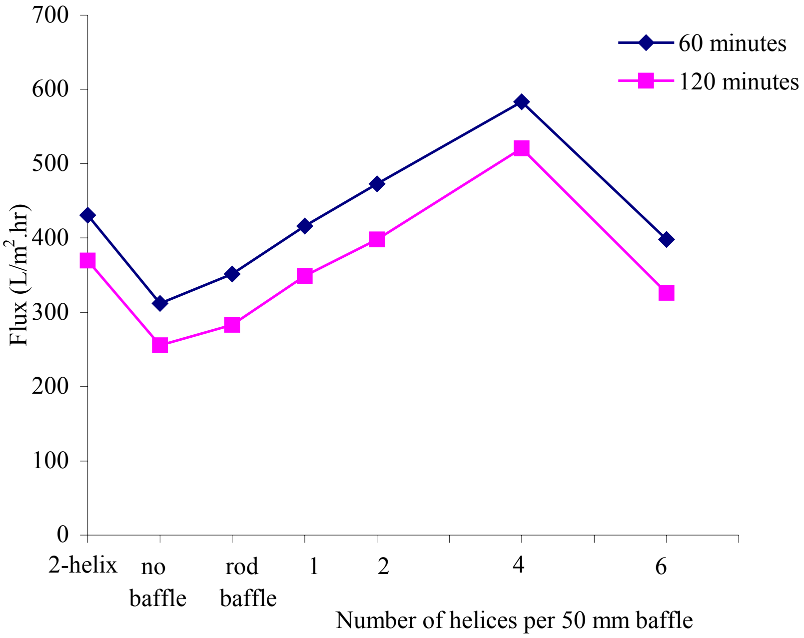


FIGURE 6 : Effect of Number of Helices on the Permeate Flux

The comparison between the average flux obtained with TiO_2 and bakers yeast solution shows that the average flux was always lower for the latter. The different pattern observed with yeast can be attributed to its compressibility or perhaps to internal fouling[27]. Yeast cells are big that they cannot penetrate into the pores of the membrane. They are also sticky and thus they tend to stick to the surface of the membrane. Thus, they form a cake layer more quickly and the flux reduction is also faster. It is also probable that the retained cells probably form concentration polarization or cake layers more quickly than the TiO_2 dispersions. The soluble components can absorb to the membrane surface and to the pore walls and plug the pores or they can bind to the cake layer making it tighter and less permeable compared to TiO_2 dispersions. This study shows that the versatility of the baffles that increases the permeate flux considerably in inorganic feed (TiO_2) as well as in organic feeds (bakers yeast).

4. Conclusion

This research demonstrates that, under properly defined operating conditions, the use of helical shape baffle is able to provide an increase in permeate flux. Helical baffles of different geometries i.e. 1, 2, 4, 6 per 50 mm baffle length give varying increase in flux. In this research, the highest flux is obtained for the 4 turns per 50 mm baffle length. Helical baffles generate helical flow and increases flow turbulence. This helical flow develops a scouring action which reduced surface concentration and enhances permeate flux. It is proven that helical baffles could be applied for inorganic as well as organic feeds. Manufacturing and installation of this type of baffle was proved to be easy and simple. Thus, the use of helical baffles to combat membrane fouling in microfiltration is perfectly justified.

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