Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

Flux Enhancement by Introducing Turbulence Effect for Microfiltration of *Saccharomyces cerevisiae*

A. L. Ahmad[a]; A. Mariadas[a]; K. K. Lau[a]
[a] School of Chemical Engineering, Universiti Sains Malaysia, Penang, Malaysia

To cite this Article Ahmad, A. L. , Mariadas, A. and Lau, K. K.(2005) 'Flux Enhancement by Introducing Turbulence Effect for Microfiltration of *Saccharomyces cerevisiae*', Separation Science and Technology, 40: 6, 1213 — 1225
To link to this Article: DOI: 10.1081/SS-200052788
URL: http://dx.doi.org/10.1081/SS-200052788

Separation Science and Technology, 40: 1213–1225, 2005

ISSN 0149-6395 print/1520-5754 online
DOI: 10.1081/SS-200052788

Flux Enhancement by Introducing Turbulence Effect for Microfiltration of *Saccharomyces cerevisiae*

A. L. Ahmad, A. Mariadas, and K. K. Lau
School of Chemical Engineering, Universiti Sains Malaysia,
Engineering Campus, Penang, Malaysia

Abstract: Numerous studies have proven that the existence of turbulence effect could promote flux enhancement in the crossflow microfiltration channel. These turbulence effects can be generated by the introduction of turbulence promoters like helical baffles. 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 turbulence effects in the feed channel on permeate flux during the microfiltration of *Saccharomyces cerevisiae* solutions. Tubular, single channel ceramic membranes with a nominal pore size of 0.2 μm were used. Variations of the helical baffle geometries, which are the number of turns per baffle length, were investigated. It was found that the insertion of helical baffles managed to increase the permeate flux. The optimum number of turns is four turns per 50 mm, which demonstrated the lowest cake resistance, R_c, and highest permeation flux, J, for particular transmembrane pressure, ΔP. The increment of permeation flux reaches 88.2% while the cake resistance is reduced to 70.62% compared to the run without baffles.

Keywords: Turbulence effects, microfiltration, reduced cake resistance, helical baffles, *Saccharomyces cerevisiae*

Received 31 August 2004, Accepted 7 January 2005
Address correspondence to A. L. Ahmad, School of Chemical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Seberang Prai Selatan, Penang, Malaysia. Fax: +604-5941013; E-mail: chlatif@eng.usm.my

1. INTRODUCTION

Since the 1960s, the search for viable alternatives to traditional energy-intensive separation methods, such as distillation, has led to the introduction of processes based on membranes. Crossflow microfiltration is a pressure-driven process that is widely used in purifying, concentrating, or separating macromolecules, colloids, and suspended particles from solution (1–3). Recently, ceramic membranes have found a 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 (4). 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 (5, 6). In the effort of reducing and eliminating membrane fouling, a number of measures have been introduced by several researchers. These include applying electrophoretic and electroosmosis effects by using an electric field (7–10), Transmembrane Pressure Pulsing (TPP) by frequently and periodically reversing the transmembrane pressure (11), rapid backpulsing, and backflushing (12–14), membrane surface modification (16–18), gas sparging (19, 20), and many others.

Hydrodynamic approaches as alternative techniques have been employed to control these flux-limiting phenomena such as creating unsteady flows by pulsations using a collapsible-tube pulsation generator (21), slug flow (22), and the use of dynamic membranes (23). 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 are also turbulence promoters made from rods with intermittently spaced rings cemented onto them. These rings can also be replaced with other shapes such as square cross-section rings. These inserts can be collectively called baffles.

Turbulence can be generated by the incorporation of helical baffles in the membrane feed channel, which subsequently reduces 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. This helical flow is one that flows along the helical groove of the helical baffles. These helical vortices create fluid instabilities or turbulence in the feed and, thus, mechanically scarp the surface of the membrane. Also, helical baffles are expected to perform better than are 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 (24). Bellhouse and colleagues (24) noted that the screw-thread design generates Dean vortices, which promote good mixing of the fluids and minimizes concentration polarization effects. They found that helical inserts produced much higher fluxes at low crossflow rates than did membranes without inserts (up to a factor higher than 6).

Meanwhile, Ghaffour et al. conducted a study using helical baffles to enhance the permeate flux in crossflow ultrafiltration of supernatant that consisted of suspended and biological solids from activated sludge plants (25). This study concluded that 1 bar is an optimal pressure and above that pressure the permeation flux decreases, which is contrary to several works that observed a plateau after a certain value of pressure. They also stated that progressive fouling can be limited by the use of helical baffles in the filtration element operated at low pressures and flocculation of particles consequently is reduced.

A ceramic membrane system, which was utilized as an experimental study to evaluate flux performance and solids retention efficiency in the microfiltration (MF) of a primary municipal sewage effluent by employing a helically wound baffle installed inside the cross flow channel, also was investigated (26). The membranes 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. Gan and Allen (26) reported that by installing the helical baffle inserts inside the flow channel, a 22% flux improvement was achieved.

A study of the employment of helical baffles in membrane filtration of baker's yeast and dodecane-water emulsion was conducted (27). A mineral membrane (Carbosep, France) was used. Helical baffles with a different number of turns (1, 2, 4, 6) per 25 mm baffle length were made by winding a steel wire (1 mm diameter) on a steel rod of 3.1 or 2.3 mm diameter. The authors 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 was also carried out (28). It is reported that the use of helical baffles, under the hydrodynamic conditions, increased the permeate flux rate from $10\,L/m^2 \cdot th$ to $25\,L/m^2 \cdot h$. Furthermore, an increase of about 200% of flux was possible even with the same hydraulic dissipated power.

A tubular membrane system fitted with geometrical inserts of disc and doughnut shapes was used experimentally to create a periodically grooved channel (29). The membrane performance for these systems alone and with the combination of pulsed flow for the microfiltration of 10 to 25 g/L solution of the purified whey protein Bipro using tubular membrane were investigated. 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.

The aim of this study was to investigate the effects of using different geometries of baffles, which are the number of turns per baffle length, on the permeate flux for the microfiltration *Saccharomyces cerevisiae* solutions. Experiments were conducted using the different geometries of baffles fabricated for *Saccharomyces cerevisiae* solutions. The optimum condition for the best type of baffle is to be identified. The performance will be analyzed in term of the effect of using turbulence in the membrane channel to reduce the cake resistance formation on the membrane surface.

2. MATERIALS AND METHODS

2.1 Experimental Set-up

Figure 1 shows the laboratory scale membrane filtration rig, which consisted of a feed tank, a feed pump, a filtration unit, valves, and measuring equipment

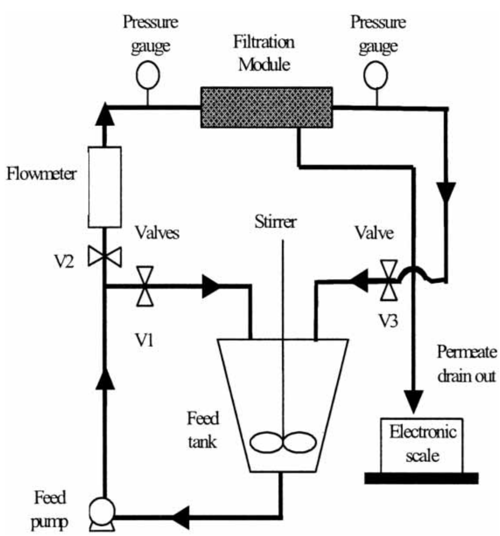

Figure 1. Schematic diagram of the flow of the microfiltration process.

such as a flow meter, pressure gauges, and an electronic balance. A tubular, single circular shape channel ceramic membrane purchased from Fairey Industrial Ceramics Limited, England, which measured 14 mm inner diameter and 600 mm long with a membrane surface area of 0.06 m^2, was used. The membrane was made of alumina with an average pore size of 0.2 μm. The properties of the ceramic membrane, as given by the manufacturer, are shown 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 possible repeated membrane regeneration after fouling.

Helical baffles of different number of turns such as 1, 2, 4, or 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 a 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 in diameter, which represents a helical baffle with an infinite number of turns, also was 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 photographic view for the different geometries of helical baffles.

The *Saccharomyces cerevisiae* used was purchased from Mauri Fermentation (M) Sdn. Bhd. as compressed yeast. The concentration of the *Saccharomyces cerevisiae* was also 1 g/L. The solution in the feed tank was

Table 1. Properties of the ceramic membrane

Material	δ-alumina
Average pore size (μm)	0.2
Porosity (vol %)	35
Flexural strength (MPa)	45
Diameter (mm)	20
Length (mm)	600
Channel:	
Circular OD (mm)	20
Circular OD (mm)	14
Star OD (mm)	14
Star ID (mm)	maximum
Filtration area (m^2)	0.06
pH range	0.5–13.5
Maximum temperature (°C)	140
Maximum pressure (bar)	8

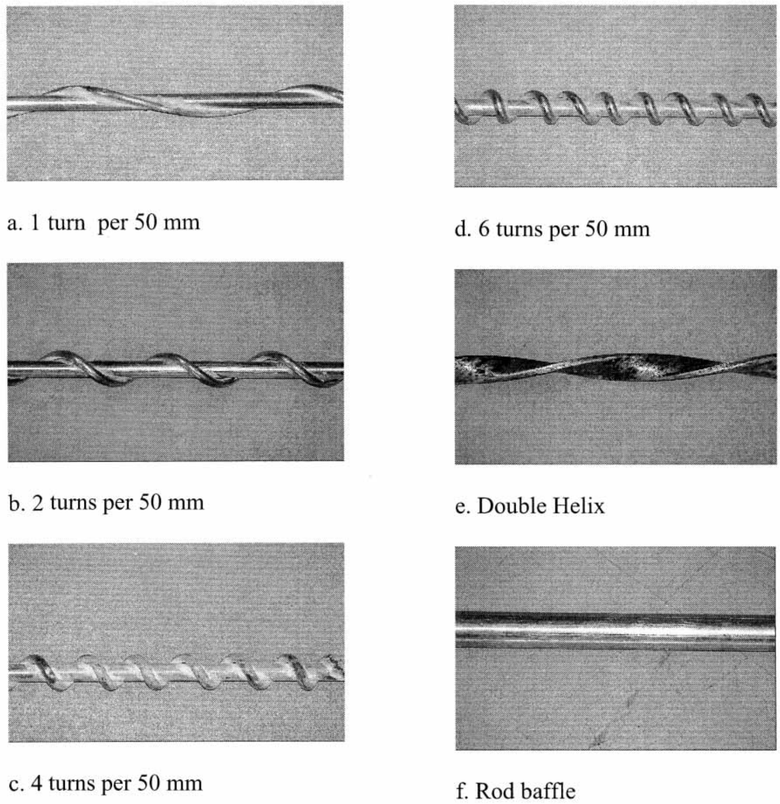

Figure 2. Photographic view of different geometries of helical baffles.

continuously recirculated to get better mixing and dispersion with the help of a stirrer. Particle size distribution (PSD) measurements were done by using a Malvern Laser Diffaction Instrument (Malvern Mastersizer E). The ceramic membranes were cleaned after each experiment in order to restore the pure water flux of the membrane 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°C using 1% w/w NaOH solution with the addition of 5 g/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 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, or 6 per 50 mm baffle length. Each experiment ran for two hours.

The permeate was collected every 5 minutes for the first hour and every 10 minutes for the subsequent hour. The weight of the permeate was measured by using an electronic balance. The permeate flux was constantly returned to the feed tank as was the retentate in order to maintain a constant inlet feed concentration. Each set of the experiment was repeated five times and the average value was taken in order to have reproducible and repeatable data.

2.2 Parameters for Membrane Resistance

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

$$J = \frac{1}{\mu R_m} \Delta P \tag{1}$$

From Eq. (1), the slope for the plot J vs. ΔP gives the value for $\{1/\mu R_m\}$. The value of R_m can be determined when the μ is known.

The value for R_c can be calculated by using the following equation:

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

From Eq. (2), the slope for the plot J vs. ΔP gives the value for $1/\mu(R_m + R_c)$. (With the value of R_m), which was computed from Eq. (1), the value of R_c could be evaluated from the slope in Eq. (2).

3. RESULT AND DISCUSSION

The average particle size for *Saccharomyces cerevisiae* was 1.56 μm. Thus, the average size of the particle in the feed stream is bigger than is 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 *Saccharomyces cerevisiae* at 20 psi TMP. It is clearly shown that the four turns per 50 mm helical baffle gives the highest average flux at 214.6 L/$m^2 \cdot$ hr, an increase of 88.2% compared to the run without any baffles that will produce an average flux of 114.0 L/$m^2 \cdot$ hr. The two 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%), one turn per 50 mm (58.7%), six turns per 50 mm (55.9%), and finally the rod baffle (52.9%). Figures 3 and 4 clearly show that

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

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

the average flux for the run with *Saccharomyces cerevisiae* is always higher with the presence of baffles. This also proves that the presence of baffle reduces membrane fouling and thus increases the flux (Table 3).

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, 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 (30). This will eventually reduce the formation of filter

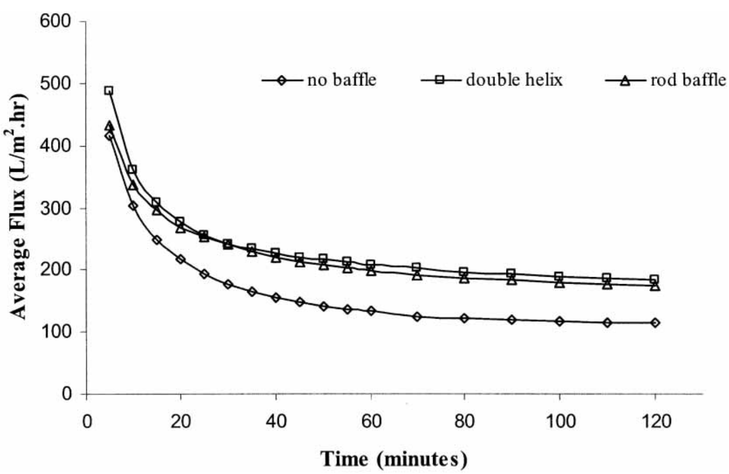

Figure 3. Flux performance for the run with two helix baffle, rod baffle, and without baffle for 1 g/L *Saccharomyces cerevisiae* at 20 psi TMP.

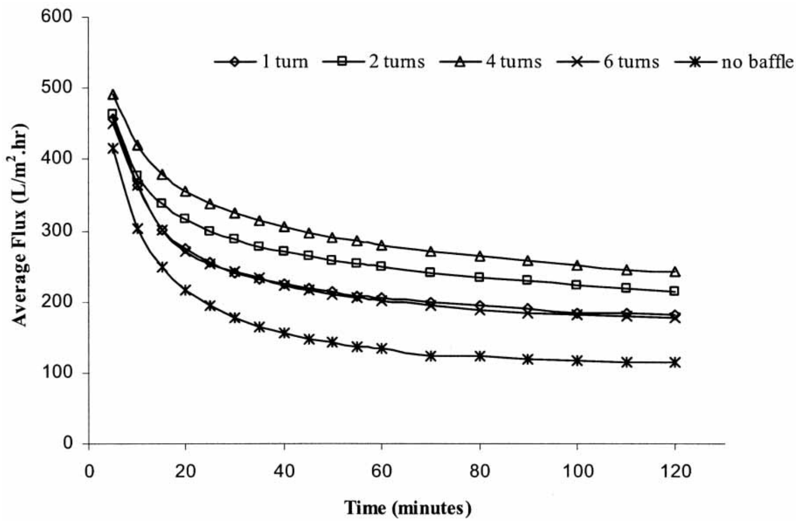

Figure 4. Flux performance for the run with 1 turn/50 mm baffle, 2 turns/50 mm baffle, 4 turns/50 mm baffle, 6 turns/50 mm baffle, and without baffle for 1 g/L *Saccharomyces cerevisiae* at 20 psi TMP.

cake on the surface of the membrane. The insertion of a helical baffle changed the flow field. A major rotational component probably exists and the particle deposition rate on the membrane surface decreases with the presence of helical baffles (28). 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

Table 3. Cake resistance for different type of baffles

Baffle	$R_c \times 10^{-11}$ (m^{-1})	Percentage of reduction compared to run without baffles
1 turn/50 mm baffle	2.281	44.06%
2 turns/50 mm baffle	1.805	55.74%
4 turns/50 mm baffle	1.800	55.85%
6 turns/50 mm baffle	2.336	42.71%
Double helix	2.228	45.37%
Rod baffle	2.397	41.22%
Without baffle	4.077	0

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 *Saccharomyces cerevisiae* solutions.

Gupta et al. conducted similar experiment with different shapes of baffles (27). The authors showed that there was an optimum baffle shape that generates optimum flux. Hence, it is believed that the optimum shape of baffle for this study is 4 turns/500 mm due to its highest permeates flux. A lower number of turns per length of baffle will generate less helical turbulence flow due to the insufficient scouring screws on the baffle rod that occurred in the run of 1 turn/50 mm and 2 turns/50 mm. When the number of turns is increased until 6 turns/50 mm, the permeate flux will decrease because the increase in the number of turns will end up with a geometry that approaches the rod geometry. The rod baffle generates the lowest flux compared to the any other types of helical baffle. Rod baffles tend to generate laminar flow instead of turbulence flow. Inadequate helical turbulent flow promotes the formation of the fouling layer and subsequently reduces the permeate flux. For optimum number of turn per length of baffle (4 turns/50 mm), it has an optimum of number of screws and distance between the screws on the baffle rod to generate maximum turbulent helical flow that consequently yields the highest permeate flux.

The resistance of the clean membrane, R_m, was found to be $7.807 \times 10^{10}\,m^{-1}$ by using Eq. (1). Based on these values (Table 3), it is clearly seen that the value of R_c, the membrane resistance due to gels, cakes, and adsorption is the lowest for the 4 turns/50 mm baffle and the highest for the run without any baffles. There is a decrease of 55.85% in the membrane resistance due to gels, cakes, and adsorption, R_c, when the 4 turns/50 mm baffle is used as compared to the run without baffles. For the other baffles, the percentage decreases are as follows: 44.06% for the 1 turn/50 mm baffle, 55.74% for the 2 turns/50 mm baffle, 42.71% for the 6 turns/50 mm baffle, 45.37% for the double helix baffle, and 41.2% for the rod baffle.

From Fig. 5, it can be observed that a higher flux gives a lower R_c value and vice versa. For example, the 4 turns/50 mm baffle has the highest flux and it also has the lowest R_c value. This figure also shows that membrane fouling was least in the 4 turns/50 mm baffle and greatest in the run without any baffles. This result further strengthens the case that when a helical baffle is used, it generates a helical turbulent flow field, which probably scours the surface of the membrane more than in the case when a baffle is not present. The turbulent scouring effect when helical baffles are used may directly remove particles from the surface, thus reducing R_c. Also the mass transfer boundary layer thickness will be reduced, thus increase the mass transfer away from the surface, which will reduce the surface concentration. This reduction is also probably responsible for the reduction in R_c.

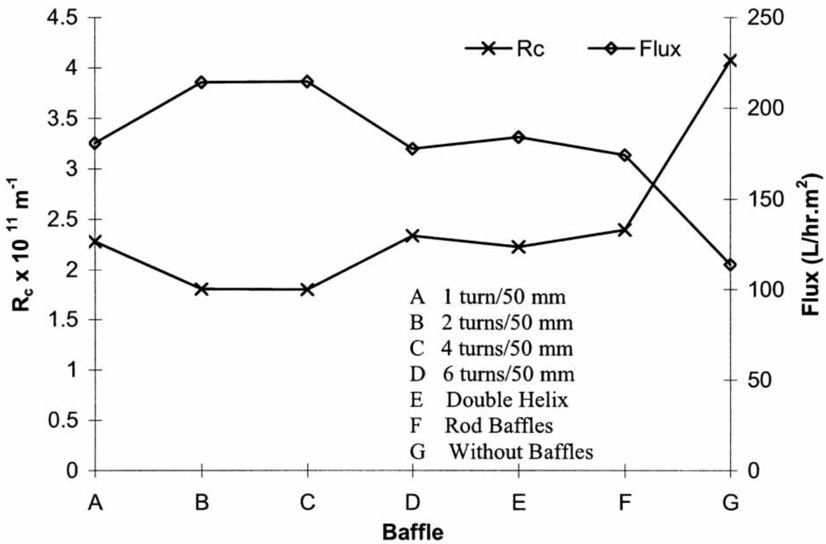

Figure 5. Comparisons of R_c and permeate flux for different types of baffles.

4. CONCLUSION

The use of a helically shaped baffle is plausible to provide an increase in permeate flux under properly defined operating conditions. Helical baffles of different geometries, i.e., 1, 2, 4, or 6 per 50 mm baffle length give varying increases in flux. For this work, the highest flux is obtained for the 4 turns per 50 mm baffle length. This optimum number of turns per length of baffle also generates the lowest membrane cake resistance, R_c, which proves that this optimum configuration managed to reduced membrane fouling efficiently and it yields the highest permeate flux. Helical baffles generate helical flow and increases flow turbulence. This helical turbulent flow develops a scouring action that reduces membrane cake resistance and enhances permeate flux. Manufacturing and installation of this type of baffle proved to be easy and simple. Thus, the use of helical baffles to combat membrane fouling in microfiltration is perfectly justified.

NOMENCLATURE

J average flux ($L/m^2 \cdot hr$)
ΔP transmembrane pressure (TMP) (psi)

R_c membrane resistance due to gels, cake, and adsorption (m^{-1})
R_m clean membrane resistance (m^{-1})

Greek Letter

μ viscosity of the feed ($Pa \cdot s$)

REFERENCES

1. Keskinler, B., Yildiz, E., Erhan, E., Dogru, M., Bayhan, Y.K., and Akay, G. (2004) Cross flow microfiltration of low concentration-nonliving yeast suspensions. *J. Membr. Sci.*, 233: 59–69.
2. Cho, C.W., Lee, D.Y., and Kim, C.W. (2003) Concentration and purification of soluble pectin from mandarin peels using crossflow microfiltration system. *Carbohyd. Polym.*, 54: 21–26.
3. Mikulášek, P., Doleček, P., Šmídová, D., and Pospíšil, P. (2004) Crossflow microfiltration of mineral dispersions using ceramic membranes. *Desalination*, 163: 333–343.
4. Liang, Y.C., Jian, J.Q., Wen, M.C., Pei, K.L., and Xiao, Z.L. (2000) Enhanced performance for crossflow microfiltration processes with tubular ceramic membrane. *Filtr. Separat.*, 8: 36–40.
5. Broussous, L., Prouzet, E., Beque, L., and Larbot, A. (2001) An experimental study of helically stamped ceramic microfiltration membranes using bentonite suspensions. *Sep. Purif. Techol.*, 24: 205–221.
6. de Barros, S.T.D., Andrade, C.M.G., Mendes, E.S., and Peres, L. (2000) Study of fouling mechanism in pineapple juice. *J. Membr. Sc.*, 5561: 1–12.
7. Weigert, T., Altmann, J., and Ripperger, S. (1999) Crossflow electrofiltration in pilot scale. *J. Membr. Sci.*, 159: 253–262.
8. Iritani, E., Mukai, Y., and Kiyotomo, Y. (2000) Effects of electric field on dynamic behaviors of dead-end inclined and downward ultrafiltration of protein solutions. *J. Membr. Sci.*, 164: 51–57.
9. Bowen, W.R. and Ahmad, A.L. (1997) Pulsed electrophoretic filter cake released in dead-end membrane processes. *J. AIChE.*, 43: 959–970.
10. Ahmad, A.L., Ibrahim, N., and Bowen, W.R. (2002) Automated electrophoretic membrane cleaning for dead end microfiltration and ultrafiltration. *J. Sep. & Purif. Technol.*, 29: 105–112.
11. Jones, W.F., Valentine, R.L., and Rogers, V.G.J. (1999) Removal of suspended clay from water using transmembrane pressure pulsing. *J. Membr. Sci.*, 157: 199–210.
12. Serra, C., Durand-Bourlier, L., Clifton, M.J., Moulin, P., Rouch, J.-C., and Aptel, P. (1999) Use of air sparging to improve backwash efficiency in hollow-fiber modules. *J. Membr. Sci.*, 161: 95–113.
13. Srijaroonrat, P., Julien, E., and Aurelle, Y. (2000) Unstable secondary oil/water emulsion treatment using ultrafiltration: fouling control by backflushing. *J. Membr. Sci.*, 159: 11–20.
14. Mores, W.D., Bowman, C.N., and Davies, R.H. (2000) Theoretical and experimental flux maximization by optimization of backpulsing. *J. Membr. Sci.*, 165: 225–236.

15. Sondhi, R., Lin, Y.S., and Alverez, F. (2000) Crossflow filtration of chromium hydroxide suspension by ceramic membranes: fouling and its minimization by backpulsing. *J. Membr. Sci.*, 174: 111–122.
16. Nabe, A., Staude, E., and Belfort, G. (1997) Surface modification of polysulfone ultrafiltration membranes and fouling by BSA solutions. *J. Membr. Sci.*, 133: 57–72.
17. Hamza, A., Pham, V.A., Matsuura, T., and Santerre, J.P. (1997) Development of membranes with low surface energy to reduce the fouling in ultrafiltration applications. *J. Membr. Sci.*, 131: 217–227.
18. Ma, H., Bowman, C.N., and Davis, R.H. (2000) Membrane fouling reduction by backpulsing and surface modification. *J. Membr. Sci.*, 173: 191–200.
19. Cui, Z.F. and Wright, K.I.T. (1996) Flux enhancements with gas sparging in downwards crossflow ultrafiltration: performance and mechanism. *J. Membr. Sci.*, 117: 109–116.
20. Bellara, S.R., Cui, Z.F., and Pepper, D.S. (1996) Gas sparging to enhance permeate flux in ultrafiltration using hollow fibre membranes. *J. Membr. Sci.*, 121: 175–184.
21. Hadzismajlovic, D.E. and Bertram, C.D. (1999) Flux enhancement in turbulent crossflow microfiltration of yeast using a collapsible-tube pulsation generator. *J. Membr. Sci.*, 163: 123–134.
22. Mercier, M., Fonade, C., and Lafforgue-Delorme, C. (1997) How slug flow can enhance the ultrafiltration flux in mineral tubular membranes. *J. Membr. Sci.*, 128: 103–113.
23. Ał Malack, M. and Anderson, G.K. (1996) Formation of dynamic membranes with crossflow microfiltration. *J. Membr. Sci.*, 112: 287–296.
24. Bellhouse, B.J., Costigan, G., Abinava, K., and Merry, A. (2001) The performance of helical-thread inserts in tubular membranes. *Sep. Purif. Technol.*, 22–23: 89–113.
25. Ghaffour, N., Jassim, R., and Khir, T. (2004) Flux enhancement by using helical baffles in ultrafiltration of suspended solids. *Desalination*, 167: 201–207.
26. Gan, Q. and Allen, S.J. (1999) Crossflow microfiltration of a primary sewage effluent- solids retentation efficiency and flux enhancement. *J. Chem. Technol. Bio.*, 74: 693–699.
27. Gupta, B.B., Howell, J.A., Wu, D., and Field, R.W. (1995) A helical baffle for cross-flow microfiltration. *J. Membr. Sci.*, 99: 31–42.
28. Gupta, B.B. and Enfert, E. (1996) Use of a helical baffle for red wine clarification on mineral membrane. *Separ. Sci. Technol.*, 31 (20): 2775–2789.
29. Finnigan, S.M. and Howell, J.A. (1998) The effect of pulsatile flow on ultrafiltration fluxes in a baffled tubular membrane system. *Chem. Eng. Res. Des.*, 67: 278.
30. Sablani, S.S., Goosen, M.F.A., Al-Belushi, R., and Wilf, M. (2001) Concentration polarization in ultrafiltration and revese osmosis: a critical review. *Desalination*, 141: 269–289.