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Kenics Static Mixer as Turbulence Promoter in Cross-Flow Microfiltration of Skim Milk

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ABSTRACT

The efficiency of cross-flow membrane filtration processes is limited by membrane fouling and concentration polarization. The question of membrane fouling and membrane pore blocking during microfiltration is much more important than in the traditional ultrafiltration, not only for the maintenance of acceptable flux but also for the adequate recovery of the permeate components. The objective of this study was to demonstrate that use of a static mixer as turbulence promoter results in enhanced cross-flow microfiltration of skim milk. Experimental investigations were performed on 50-nm and 100-nm ceramic tubular membranes. The use of a static mixer provided a significant reduction of membrane fouling and an increase of more than 700% in permeate flux for both membranes compared with that obtained without a static mixer at the same feed flow rate. The similar flux enhancement indicates that surface layer resistance dominates the overall fouling resistance. Although the power consumption was significantly increased by using a static mixer, a decrease of

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more than 25% in specific energy consumption for both membranes was achieved with static mixer as compared to arrangement without static mixer in experiments performed at the same cross-flow velocity.

Key Words: Cross-flow microfiltration; Static mixer; Flux improvement; Skim milk.

INTRODUCTION

The microfiltration and ultrafiltration of protein solutions is characterized by a decline in the permeate flux with filtration time because of concentration polarization and progressive membrane fouling. Enhanced permeate fluxes of the order of 2 or more have been obtained by applying hydrodynamic methods, such as the use of static turbulence promoters with or without superimposing pulsations for creating unsteady flow.[1−7] Most of these techniques have been applied to mineral membranes which can withstand high variations of transmembrane pressure and high temperatures.

The Kenics static mixers, together with the SMX mixers, are the most common static mixers in industry. The Kenics static mixer (Fig. 1) consists of a series of mixing elements inserted inside the whole membrane tube. The mixing elements are made from thin, flat strips, twisted through 180° to form helices of alternating left and righthand rotations. The flow field is caused to rotate, or swirl, by the helical nature of the elements. In addition, the periodic alternation of the flow establishes the generation of vortices which further increase the wall shear rate, thereby reducing concentration polarization and increasing the scouring of the membrane surface more than in the case of an empty tube.

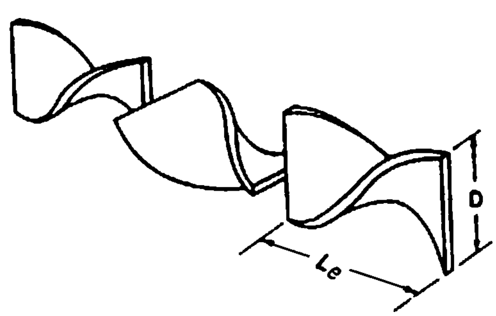

Figure 1. Kenics static mixer.

Some studies on the use of Kenics static mixers as turbulence promoters in cross-flow membrane processes have been reported in the literature.[6,7] Vatai and Tekić[6] used the Kenics static mixer as turbulence promoter in ceramic membrane during cross-flow ultrafiltration of aqueous solutions of sodium carboxymethylcellulose and pectin. They observed a significant decrease of gel layer concentration at the membrane surface. As the result of this concentration decrease, the permeate flux was increased about 300%. Sugimoto et al.[7] used a twisted tape and Kenics static mixer as turbulence promoters during cross-flow ultrafiltration of dextran T500 aqueous solution. The permeate flux of a membrane module fitted with a twisted tape was 300% higher than that of a membrane module without any turbulence promoter. Flux improvements with the use of Kenics static mixer were as high as 670%, depending on length to diameter ratios of mixing elements. However, an increase in power consumption for fluid flow was observed because of the increase of pressure drop along the membrane module with inserted twisted tape or static mixer. The energy consumption per unit mass of permeate was 100% to 200% higher than that in the membrane module without turbulence promoter.

In this work we have investigated whether the skim milk cross-flow microfiltration performance could be improved by inserting Kenics static mixer as turbulence promoter. The effect of static mixer on permeation flux and membrane fouling was examined for ceramic membranes with pore sizes of 50 nm and 100 nm. The increase in power consumption for fluid flow resulting from the insertion of a static mixer was also examined. The two main parameters we chose to characterize the efficiency of the process were the permeate flux and the specific energy consumption.

MATERIALS AND EXPERIMENTAL PROCEDURE

The experiments were carried out on a cross-flow microfiltration unit shown on Fig. 2. The feed used throughout experiments was 10% (w/v) reconstituted dried skim milk (Subotica Dairy, Yugoslavia). Skim milk was concentrated to a volumetric concentration factor, *VCF*, of about 1.70. Volumetric concentration factor was obtained through the equation:

$$VCF = \frac{V_{ret,i}}{V_{ret,t}} \tag{1}$$

All experiments were carried out at 50±0.2°C. The mean transmembrane pressure difference was adjusted by a regulator valve (the accuracy was ± 3 kPa). The membranes studied were Membralox membranes (SCT, Bazet, France),

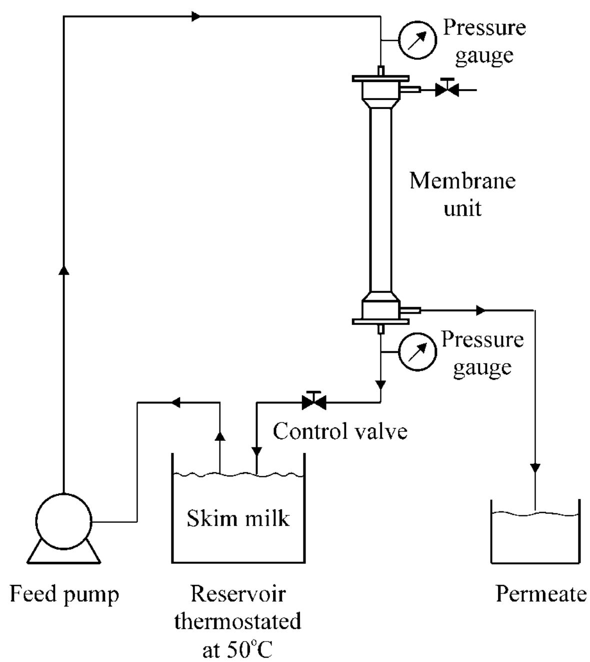

Figure 2. Experimental set-up.

single-channel type, 250 mm long, with 6.8 mm inner diameter. The membranes were of 50 and 100 nm pore diameter and were made of a zirconium oxide layer on an aluminum oxide support. The useful membrane surface was 4.62×10^{-3} m^2.

The effect of turbulence promotion on filtration performance was investigated by using Kenics static mixer (FMX8124-AC, Omega, Stamford, CT, USA), consisting of 30 elements having aspect ratio (length to diameter) of 1.

CALCULATIONS

The efficiency of the static mixer as a turbulence promoter was checked through determination of the improvement of permeation flux (*FI*), the increase in hydraulic dissipated power (*PE*) and the reduction of specific energy consumption (*ER*), defined as:

$$FI = \frac{J_{p,SM} - J_{p,NSM}}{J_{p,NSM}} \times 100 \tag{2}$$

$$PE = \frac{P_{SM} - P_{NSM}}{P_{NSM}} \times 100 \tag{3}$$

$$ER = \frac{E_{NSM} - E_{SM}}{E_{NSM}} \times 100 \tag{4}$$

The hydraulic dissipated power (*P*) and the specific energy consumption (*E*) were calculated as:

$$P = Q\Delta P \tag{5}$$

$$E = \frac{P}{J_p A} \tag{6}$$

For convenience of comparison with the experimental results obtained without a static mixer, the inner tube diameter (*D*) instead of the hydraulic mean diameter was used as the characteristic length in the Reynolds number definition:

$$Re = \frac{\rho \nu D}{\mu} \tag{7}$$

The mean cross-flow velocity (ν) was calculated from the flow rate and the actual cross-section area. The properties of skim milk used were[8]: $\rho_s = 1035\,\mathrm{kg\,m^{-3}}$ (50°C) and $\mu_s = 9.2 \times 10^{-4}\,\mathrm{Pa\,s}$ (50°C).

The overall fouling resistance to permeate flux was calculated by applying Darcy's law and the resistance in series model as follows:

$$R_f = \frac{TMP}{\mu_p J_p} - R_m \tag{8}$$

For the fouling resistance calculations the values of membrane resistances (R_m) used were $4.1 \times 10^{11}\,\mathrm{m^{-1}}$ for 50 nm membrane and $2.8 \times 10^{11}\,\mathrm{m^{-1}}$ for 100 nm membrane.[8] The averaged value of $8 \times 10^{-4}\,\mathrm{Pa\,s}$ (50°C) was used for the dynamic viscosity of permeate (μ_p).[8]

RESULTS AND DISCUSSION

The variations of the permeate flux during concentration of skim milk obtained with use of a static mixer (SM mode) and without a static mixer (NSM mode) are shown in Fig. 3. The results are shown for 50 nm pore size membrane (designated M50) and 100 nm pore size membrane (designated M100). The concentration experiments were carried out at the same mean cross-flow velocity of $1.07\,\mathrm{m\,s^{-1}}$ ($Re = 8200$) and at initial transmembrane pressure difference of 65 kPa. The insertion of the Kenics static mixer as a turbulence promoter caused a large flux improvement (more than 700%) for both membranes at examined operation conditions.

In both modes of operation (NSM and SM), the observed changes in flux during concentration were typical of the behavior of skim milk cross-flow microfiltration.[9,10] The main factor limiting the permeation

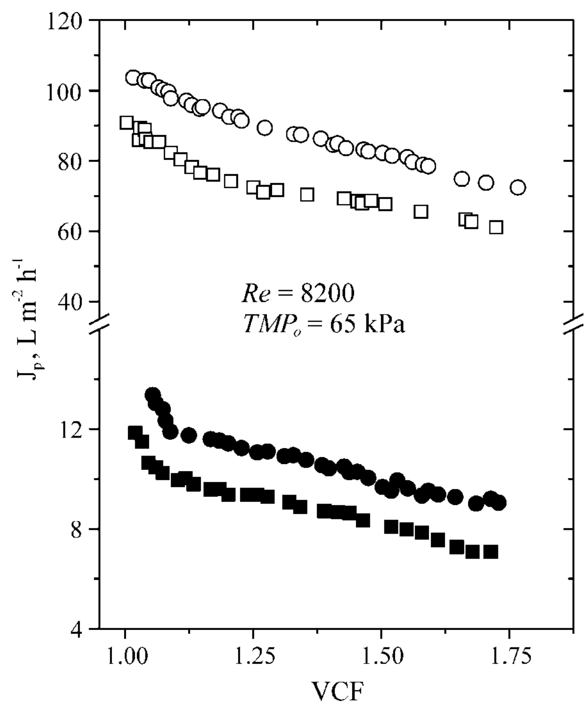

Figure 3. Variation of permeate flux with volumetric concentration factor. NSM mode: (■) M50; (●) M100. SM mode: (□) M50; (○) M100.

flux is the formation of a polarization and fouling layer on the surface of the membrane. The initial flux decline is usually attributed to concentration polarization and rapid formation of fouling deposit; the first stage appeared to be initial adsorption of a thin film of protein constituents on the membrane material,[8,11] followed by the formation of a dynamic membrane from retained casein micelles.[8,12] Increasing the feed concentration during operation resulted in further decrease in the permeate flux.

Normally the main method of reducing concentration polarization and thickness of a dense micellar layer is to create a certain shear stress at the membrane surface. This can be done by using high cross-flow velocities. In cross-flow microfiltration of skim milk, the use of high cross-flow velocities ($4-8\,m\,s^{-1}$) is necessary to achieve the long-term permeation fluxes in the range from 50 to $100\,L\,m^{-2}\,h^{-1}$.[9,10,12] As can be seen from Fig. 3, with the use of the Kenics static mixer, the preferred flux values were achieved at low cross-flow velocities ($\sim 1\,m\,s^{-1}$). The flow field generated by the static mixer increases the shear rate in the neighborhood of the membrane surface. This increased wall shear rate reduces concentration polarization and scours the surface of the membrane more than in the case of the empty tube. The enhanced scouring in the SM mode of operation probably reduces the thickness of the micellar deposit on the membrane surface, leading to large improvement of the permeate flux.

Cross-flow microfiltration results and fouling resistance calculations carried out on the same membranes with recirculation of the permeate into the feed reservoir ($VCF = 1$)[8] showed that the formation of a polarization and fouling layer on the membrane surface is the main factor limiting the permeation flux.

The observed flux improvements with the introduction of the mixer and similar flux behavior for both membranes are in agreement with the recirculation experiments and prove that the microfiltration performance is essentially limited by concentration polarization and formation of the surface micellar layer. To further verify this assumption, the corresponding overall fouling resistances were determined. To eliminate the influence of different membrane resistances, the commonly accepted normalized values of fouling resistances (R_f/R_m) were calculated.

In Fig. 4, the normalized overall fouling resistances (R_f/R_m) are plotted vs. the filtered volume (V_{fil}) for both membranes studied. The observed linear evolution confirms that surface layer resistance dominates the overall fouling resistance and that permeability is mainly limited by concentration polarization and micellar cake buildup over the membrane surface.[13]

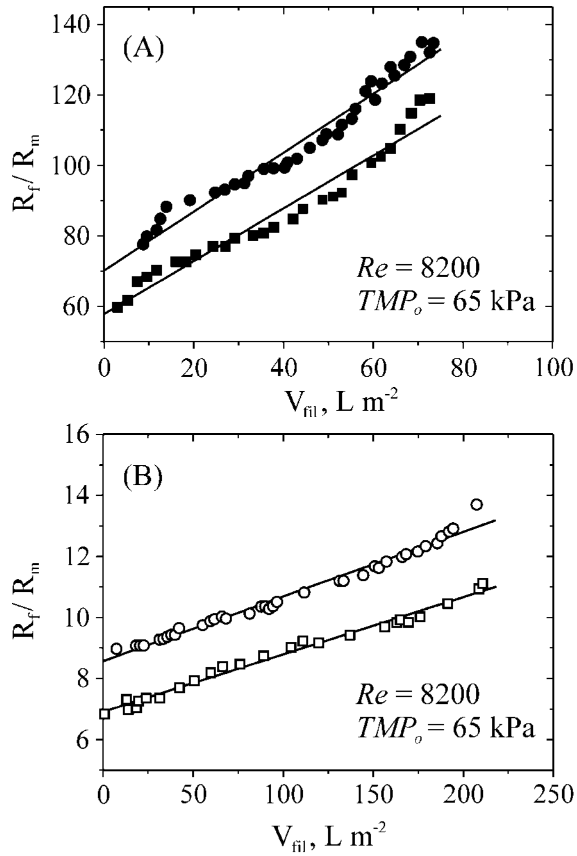

Figure 4. Normalized overall fouling resistance (R_f/R_m) vs. filtered volume (V_{fil}) for (A) NSM mode and (B) SM mode. $R_f/R_m = a{\cdot}V_{fil} + b$. NSM mode: (■) M50, $a = 57.8$, $b = 0.750$, $r^2 = 0.96$; (●) M100, $a = 70.2$, $b = 0.836$, $r^2 = 0.96$. SM mode: (□) M50, $a = 6.91$, $b = 0.019$, $r^2 = 0.99$; (○) M100, $a = 8.57$, $b = 0.021$, $r^2 = 0.99$.

Inserting a turbulence promoter in a tubular membrane causes an increase in flow velocity and pressure drop for the same feed flow rate. The permeate flux increases because of the increase in the tangential velocity, but at the same time the hydraulic dissipated power (P) increases because of increase in pressure drop along the module. Inserting the Kenics static mixer caused an increase of about 300% in frictional pressure drop along the membrane for a given feed flow rate. Therefore, the improved performance was checked with the consideration of energy consumption. Hence, the flux improvement (FI), the increase in hydraulic dissipated power (*PE*) and the reduction of specific energy consumption (*ER*) were calculated. The calculated values of these parameters for M100 membrane are shown in Table 1. Similar results were obtained for M50 membrane (data not shown).

Flux improvements of more than 700% were achieved for both membranes by using the Kenics static mixer in the range of *VCF* in the range of 1 to 1.65. The improvement in permeate flux resulted in decrease of filtration time. The time needed to achieve *VCF* of 1.65 in the SM mode was 64% shorter than in the case of NSM mode of operation for M100 membrane. The reduction of filtration time for M50 membrane was 63%.

As can be seen from Table 1, the hydraulic dissipated power slowly increased during feed concentration. This can be attributed to slow increase of mean transmembrane pressure during filtration. For *VCF* of 1.65 the observed increases of TMP were 10% and 4% for NSM and SM modes, respectively. Insertion of the static mixer caused an increase of hydraulic dissipated power of about 500% for all examined *VCF* values.

The most important parameter from an economic point of view is the specific hydraulic energy consumed (*E*). During concentration the specific energy consumption gradually increased as permeate flux decreased and hydraulic dissipated power slowly increased. As can be seen from Table 1, the decrease of more than 25% in specific energy consumption was achieved with static mixer as compared with arrangement without static mixer. Similar values of *ER* were calculated for M50 membrane. Therefore, the insertion of the static mixer, though raising the hydraulic dissipated power, can greatly enhance the permeate flux and to some extent decrease the specific energy consumption.

Table 1. Comparison of microfiltration performances of M100 membrane for NSM and SM mode of operation.

	J_p ($L\,m^{-2}\,h^{-1}$)		P (W)		E ($kWh\,m^{-3}$)				
VCF	NSM	SM	NSM	SM	NSM	SM	*FI*(%)	*PE*(%)	*ER*(%)
1.10	12	98	0.80	4.9	15	11	717	512	27
1.25	11	91	0.87	5.0	17	12	727	475	29
1.50	9.7	83	0.87	5.1	19	13	756	486	32
1.60	9.3	78	0.88	5.1	20	14	739	480	30
1.65	9.1	75	0.88	5.1	21	15	724	480	29

CONCLUSIONS

The experimental results clearly show that the improvement of permeate flux can be easily achieved by using the Kenics static mixer as a turbulence promoter without any additional equipment such as pulsating pump or any backwashing system. Improvement in permeate flux of more than 700% was obtained for both membranes studied during volumetric concentration by a factor of 1.65. Similar flux improvements, together with the fouling analysis, indicate that the formation of a polarization and fouling layer on the membrane surface is the main factor limiting the permeation flux. The flow field generated by the Kenics static mixer increases the wall shear rate, leading to enhanced scouring of the membrane surface. The enhanced scouring probably reduces the thickness of the surface micellar layer, resulting in significant reduction in membrane fouling. The use of the Kenics static mixer, although raising the hydraulic dissipated power, caused a decrease of more than 25% in specific energy consumption for both membranes as compared with an arrangement without static mixer in experiments performed at the same cross-flow velocity. These results indicate that an energy saving is possible by using the static mixer compared with operation without the mixer.

This study shows that the effect of concentration polarization and membrane fouling in cross-flow microfiltration of skim milk can by significantly reduced by using the Kenics static mixer as turbulence promoter, achieving high permeate fluxes even at low cross-flow velocities ($\sim 1\,\mathrm{m\,s^{-1}}$). Because cross-flow microfiltration of skim milk nowadays finds its practical role in dairy industry in low level of concentration (*VCF* up to 2), it appears that the use of the Kenics static mixer as turbulence promoter can significantly enhance cross-flow microfiltration of skim milk.

SYMBOLS

A	membrane area ($\mathrm{m^2}$)
D	membrane diameter (m)
E	specific energy consumption ($\mathrm{kWh\,m^{-3}}$)
ER	reduction of specific energy consumption (%)
FI	improvement of permeate flux (%)
J_p	permeate flux ($\mathrm{L\,m^{-2}\,h^{-1}}$ or $\mathrm{m\,s^{-1}}$)
M50	membrane with the mean pore size of 50 nm
M100	membrane with the mean pore size of 100 nm
NSM	without static mixer
P	hydraulic dissipated power (W)

ΔP	axial pressure drop (Pa)
PE	enlargement of hydraulic dissipated power (%)
Q	retentate flow rate (m^3 s)
R_f	overall fouling resistance (m^{-1})
R_m	membrane resistance (m^{-1})
Re	Reynolds number
SM	with static mixer
TMP	transmembrane pressure (kPa or Pa)
TMP_o	initial transmembrane pressure (kPa)
v	cross-flow velocity (m s^{-1})
V_{fil}	filtered volume (L m^{-2})
$V_{ret,i}$	initial volume of retentate (m^3)
$V_{ret,t}$	remaining volume of retentate at any time (m^3)
VCF	volumetric concentration factor
μ_p	dynamic viscosity of the permeate (Pa s)
μ_s	dynamic viscosity of the skim milk (Pa s)
ρ_s	density of the skim milk (kg m^{-3})

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