Desalination and Water Treatment
www.deswater.com

14 (2010) 227–232
February

1944-3994/1944-3986
doi: 10.5004/dwt.2010.1075

The hydrodynamic effect of microparticles on membrane resistance

Angéla Szép[a]*, Szabolcs Kertész[b], Zsuzsanna László[a], Cecilia Hodúr[a]

[a]*Department of Mechanical and Process Engineering, University of Szeged, H-6725, Szeged, Moszkvai Krt 5-7, Hungary*
[b]*School of Environmental Sciences, University of Szeged, H-6720, Szeged, Dugonics tér 13, Hungary*
Tel.: +3662 546 512; email: szangela@mk.u-szeged.hu

Received 16 July 2009; accepted 7 December 2009

ABSTRACT

The membrane technique of microfiltration (MF) was used to investigate the degree of reduction of the membrane resistance. The application of dolly-particles seems very beneficial for some MF processes with conventional equipment. A pile of bakelite enhanced the local shear near the membrane surface. This phenomenon depends greatly on the components and properties of the feed suspension; the shear force is dependent on the radius and the amount of the particles. This approach has been successful in increasing fluxes of MF. The larger particles induce a much higher shear-induced diffusion and therefore dramatically improve mass transfer. Increasing size of the bakelite particles could be associated with increasing flux.

To prevent the fouling of MF membranes during the processing of chalk-dust solutions, a high degree of turbulence should be introduced in the membrane surface. The application of microparticles (bakelite) as dolly-particles was investigated for this purpose. The experiments were carried out in MF/K1 equipment. The influence of the microparticles on the flux was investigated with a 0.45 μm tubular ceramic membrane.

The size of the bakelite particles used was 90–125 μm, 125–160 μm, 160–200 μm or 200–400 μm. It was concluded that in all cases the applied bakelite increased the permeate flux. Increasing size of the bakelite particles was associated with an increasing flux. The largest Bakelite particles (200–400 μm) caused the highest fluxes and the smallest cake resistance (R_{Cake}) and total (R_T) resistance. This work has yielded new experimental results in an alternative approach for the reduction of fouling.

Keywords: Microfiltration; Microparticles; Shearing

1. Introduction

Pressure-driven membrane separation processes (microfiltration, ultrafiltration, nanofiltration and reverse osmosis) are important and attractive alternatives to conventional treatments for the purification of wastewater and surface water. They display high removal efficiencies and also allow reuse of the treated water. These membrane techniques present a number of advantages: the purified permeate usually exhibits high quality, the processes are easy to operate at moderate temperatures and with low energy requirements in general, no chemicals are needed, and combination with other separation processes is easy because of the modular construction. A MF process is applied for the separation of particles from bulk fluids by means of membranes whose pores range in diameter from 0.1 to 10 μm [1]. They are useful for the removal of

*Corresponding author

Presented at the Fourth Membrane Science and Technology Conference of Visegrad Countries (PERMEA 2009), Prague, 7-11 June, 2009.

suspended solids, emulsified components and microorganisms larger than the pore size. Cross-flow filtration is an effective separation technology that finds application in a wide range of areas including water treatment systems, clean environment technologies and energy production. One of the numerous applications of cross-flow MF is in the food processing industry.

The particle trajectories in cross-flow filtration are considerably more complex due to the additional hydrodynamic and external forces exerted on the particle [2]. The fluid velocity profiles and particles trajectories in cross-flow filtration systems have been studied by various of researchers [3–5]. Shin [6] recently used parameters such as the particle size, Reynolds (Re) number and drag coefficient to describe the particle trajectory for a deep bed filter. Kim and Zydney [2] treated the membrane as a uniformly porous boundary and predicted particle trajectories. This work simulated the membrane as a uniformly porous medium, calculated the shear force on membrane surface, and provided a new idea for improvement of the efficiency of cross-flow MF.

The industrial applications of this technology encounter two main problems. The permeate flux (J) in MF processes decreases with time as the retained particles accumulate on the membrane [7]. The particles being filtered often foul the membrane by blocking the membrane pores and by forming a cake-layer on the membrane surface [8]. Membrane fouling caused by the adsorption of particles, pore shrinkage and blockage, the deposition of particles on the membrane surface and concentration polarization [9], and involves the irreversible alterations caused in the membrane by specific physical and/or chemical interactions between the membrane and various components [10].

Membrane fouling leads to a decrease in filtration productivity, resulting in a decrease in flux with time under operation at constant trans-membrane pressure (TMP), decreases the lifetime of the membrane modules, increases the cost of production and limits further industrial applications of membrane MF technology. Hence, methods for the alleviation of the thickness of the filter cake on the membrane surface are still key technological questions at the focus of attention in the membrane field, and many varied techniques have been suggested, such as turbulence-promoting inserts [11]. One alternative approach for the reduction of fouling is discussed here. The local shear increases near the membrane surface, thereby increasing the mass transfer of accumulated compounds back into the feed bulk. Ways of increasing the local shear rate near the membrane surface include the use of scouring/dolly-particles (bakelite) [12].

2. Materials and methods

2.1. Solution preparation

Fine bakelite particles were suspended in the 20 L 0.2 wt%. chalk-dust solution. 40 g of 125–160 μm bakelite particles, 40 g of 160–200 μm bakelite particles, or 20 g, 35 g, 40 g, or 50 g of the 200–400 μm bakelite particles were added to the 20 L chalk-dust suspension.

The resulting suspensions were well mixed and pumped into the cross-flow system by means of a circulation pump.

2.2. Particle diameter analysis of chalk-dust

Particle diameter of chalk-dust was measured by Malvern laser particle diameter distribution instrument. The average particle diameter of chalk-dust particles is 2.5–10 μm which is very similar to results of Majumdar and William [13]. The size of chalk-dust is larger than 0.45 μm of the average pore size for a microfiltration membrane. Therefore, all particles of chalk-dust suspensions will be intercepted by the membrane and form the cake on the membrane surface during the filtration. The size of bakelite particles was at least tenfold bigger than the size of chalk-dust particles what enhance the shear force.

2.3. Apparatus and method

The cross-flow microfiltration (MF/K1) unit was used for our experiments. This featured a tubular ceramic membrane, with the following attributes: 19 channels with an internal diameter of 2.5 mm, an average pore size diameter of 0.45 μm, and a total effective filtration area of 0.125 m^2. Fig. 1 outlines the flow diagram of the experimental apparatus for the permeate recycling and cross-flow filtration. Temperature was controlled through the use of cold water circulating through a tubular heat exchanger (H). The operating temperature was adjusted to 25 $\pm$ 2°C. The cross-flow velocity was set and measured with a rotameter (R). The filtration pressure was adjusted by the control valves (1, 2) and was measured via the pressure indicators (PI/1, PI/2). The TMP was applied at 100, 200, 300 kPa for determination of the TMP-dependent changes in the permeate recycling of the cross-flow filtration. Flow rates of 2, 4, 6, 8, 10 and 12 $dm^3 min^{-1}$ were utilized in this study. The Re number was in the range 1,500–5,500. The concentrated chalk-dust solution was recycled into the suspension tank. J was calculated from the volume of permeate measured with the measuring-tube.

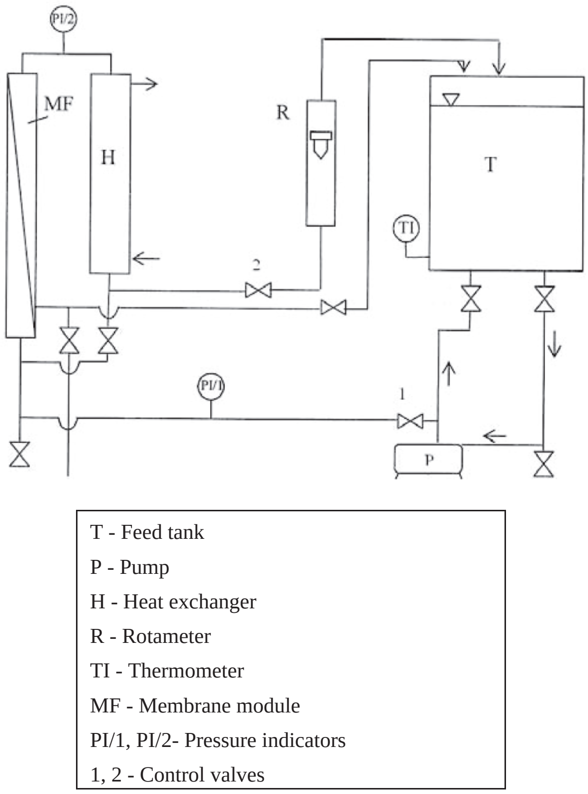

Fig. 1. MF/K1 microfiltration equipment [14].

The key factor in the pressure-driven membrane process, the flux J ($m^3\ m^{-2}s^{-1}$), can be calculated according to Darcy' s law from the transmembrane pressure TMP (Pa), the filtrate viscosity η (Pa s), and the total resistance R_T (m^{-1}) [7].

$$J = \frac{\text{TMP}}{\eta \cdot R_T} \tag{1}$$

Several additive resistances influence J. In this case, it was considered that R_T is the sum of the R_M clean membrane resistance and the R_{Cake} cake-layer resistance:

$$R_T = R_M + R_{Cake} \tag{2}$$

Before each experiment, the water flux J_W was measured with distilled water at 20°C.

The membrane resistance R_M (m^{-1}) was also defined:

$$R_M = \frac{\text{TMP}}{\eta_W \cdot J_W} \tag{3}$$

where η_W is the dynamic viscosity of water (Pa s).

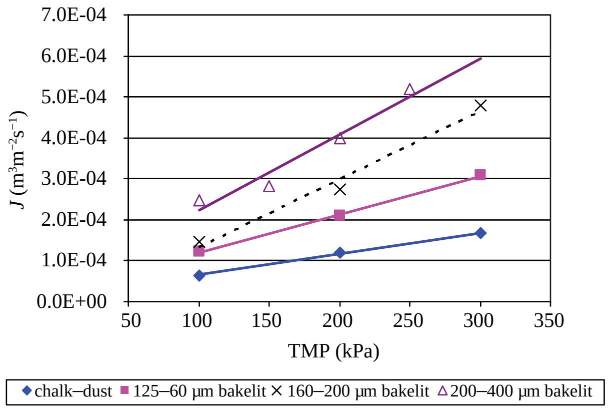

Fig. 2. Variations in J at different TMPs.

Membrane regeneration was achieved by washing in a 10 g L^{-1} NaOH solution and rinsing with distilled water under flux.

For the Re numbers, the following equation was used:

$$\text{Re} = \frac{d \cdot v \cdot \rho}{\eta} \tag{4}$$

where d is the pipe diameter (m), the v is the velocity (m/s), the ρ is the density (kg/m^3) and the η is the viscosity (Pa s) of fluid.

Turbidity ratio (TR):

$$\text{TR} = \frac{\text{Turbidity of samples}}{\text{Turbidity of control}} \tag{5}$$

where the "sample" is the permeate from the bakelite-containing feed, and the "control" is the permeate filtered without the presence of the bakelite.

3. Results and discussion

The relation between J and TMP was measured for the different particles suspended in the chalk-dust solution. The results are presented in Fig. 2.

The operation parameters included three different TMPs, 100, 200 and 300 kPa; three different particle diameter ranges: 125–160 μm, 160–200 μm and 200–400 μm; and chalk-dust solution with or without bakelite. There was a linear relationship between the J and the TMP difference in each case. The J values of the chalk-dust solution were always lower than that of the bakelite suspension because the bakelite particles caused turbulence on the surface of the membrane. Due to the greater shearing on the membrane surface, the thickness of the cake-layer was reduced and the molecules of the solvent could pass through the

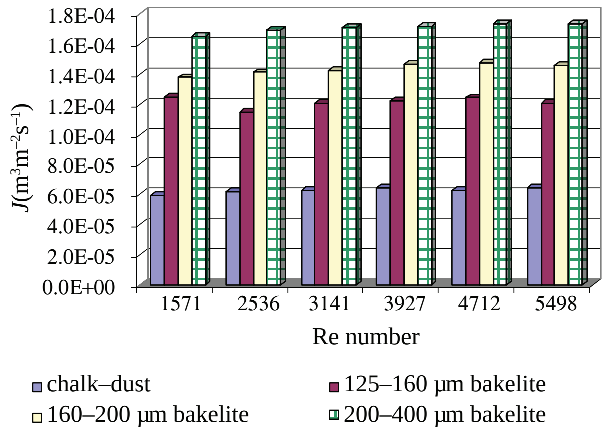

Fig. 3. Variation in J with the Re number.

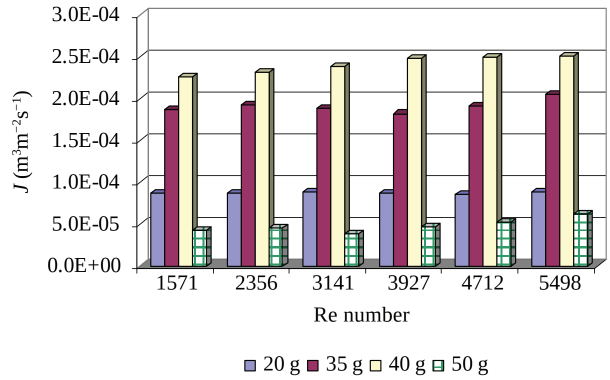

Fig. 4. Variation in J with the amount of bakelite added (dose of bakelite per 20 L of chalk-dust suspension).

membrane pores more easily. We measured the lowest J values for the 125–160 µm bakelite particles. Increasing diameter of the particles caused an increase in J. We observed the best J values with the 200–400 µm bakelite particles, and the shearing force was therefore the largest in that case.

We examined the hydrodynamic effect via calculation of the Re numbers. Increase in the Re number caused hardly any increase in J (Fig. 3). Different J values were measured when pile of bakelite were used in spite of the fact that the Re number was the same. These data showed that the effect of the pile of dolly-particles developed in the cake-layer.

The Re numbers lie in the laminar and transitional range, but the bakelite particles caused local turbulence on the surface of the membrane, as shown by the higher J values. The higher the diameter of the particle, the higher the hydrodynamic shear force, and hence the higher the value of J.

As the best J values were observed with the 200–400 µm bakelite particles, the following tests were performed with this size range.

The effects of the amount of added bakelite on J were measured (Fig. 4).

A larger quantity of bakelite particles caused a higher J value because of the bigger shear force induced. There is an optimum curve between the amount of dolly-particles and J. We observed the best J values when at 40 g of bakelite particles was used; further increase up to 50 g caused a dramatic deterioration.

The presence of the bakelite particles aced not only on the value of J, but also on the permeate turbidity. We calculated the TRs of various permeate samples (Fig. 5). The clarity and the transmittance of the samples were better than those of the control, i.e. TR < 1 (see Eq. 5). The best values were measured for the 200–400 µm fraction.

From the slopes of the lines produced via Eq. (5), the total resistance (R_T) can be calculated (Fig. 6) [15].

$$J \cdot \eta = \frac{1}{R_T} \cdot TMP \qquad (6)$$

Fig. 7 demonstrates that R_T and the R_{Cake} are significant higher with chalk-dust solution. It was speculated that, as a particle is deposited on the membrane, the next particle is deposited on it and the following particles accumulate on them to form a cake. If this process is very fast, a cake will form rapidly and the efficiency of the filtration will be reduced. It is important that a high shear force on the membrane surface can postpone the formation of the first layer of cake. In consequence of the high shear force induced by the high cross-flow velocity, the overall resistance was low. R_T was the lowest with the 200–400 µm bakelite particles, which therefore resulted in the highest shearing force

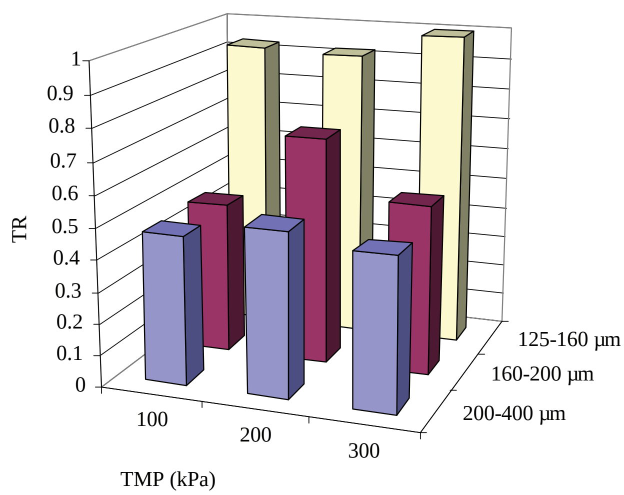

Fig. 5. Variation in TR with TMP for different bakelite particle ranges (bakelite dose 40 g).

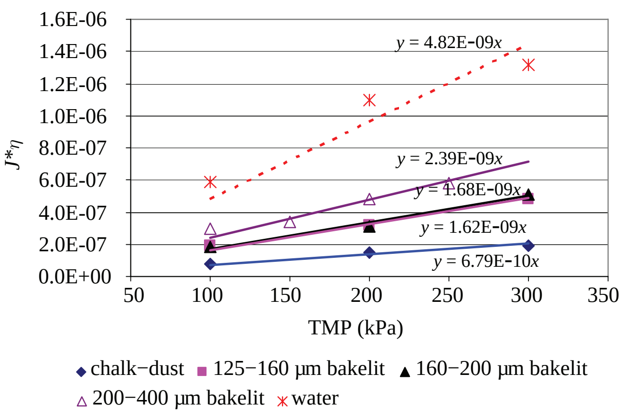

Fig. 6. The total resistance (R_T) determination by fitted lines.

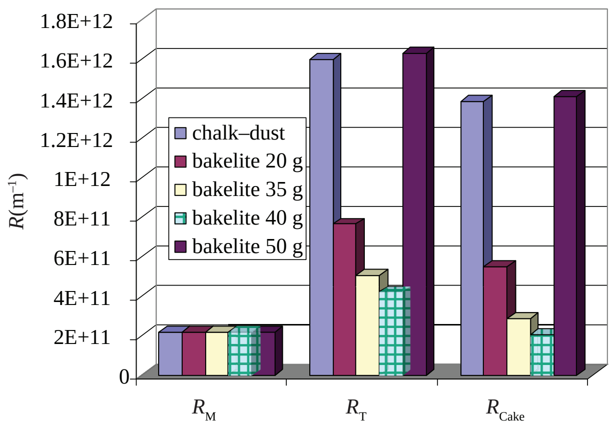

Fig. 8. Comparison of resistance values with different amounts of bakelite (200–400 μm) particles.

on the membrane surface, thereby decreasing the thickness of the cake. The R_M values were similar in all cases, because the membrane purification was efficient.

Fig. 8 reveals, that R_T and the R_{Cake} were significantly higher with 50 g of bakelite, because the bakelite particles deposited on the cake-layer enhanced the thickness of the cake-layer. R_T and R_C were the lowest with 40 g of bakelite.

4. Conclusions

This work reports new results relating to an alternative approach for the reduction of fouling during MF.

The use of bakelite particles improved the performance of the membrane processes.

When dolly-particles were applied in the MF system, in some cases a 4-fold increase in J was obtained in comparison with the cross-flow filtration conditions.

A linear correlation was observed between the mass of the dolly-particles and the permeate flux. The highest *J* was achieved by using 40 g of 200–400 μm bakelite in the 20 L chalk suspension.

The experiments showed that increase of the dolly-particle mass above 50 g per 20 L suspension did not result in an increase in *J*.

The application of dolly-particles elevated *J* in spite of the same Re number developing. This *J* increasing effect of a pile of bakelite could be due to the local turbulence caused by the particles. The flow around the particle is much more turbulent on the surface of the membrane than in the bulk. This effect arises because the accelerated motion in the boundary layer makes the cake thinner, and R_{Cake} lower. R_T and R_{Cake} were significantly higher with the chalk-dust solution than with a pile of bakelite particles. Thus, the bakelite particles decreased the resistance of the filtration. The hydrodynamic shear force decays the fouling rate on the membrane and improves the efficiency of the cross-flow MF.

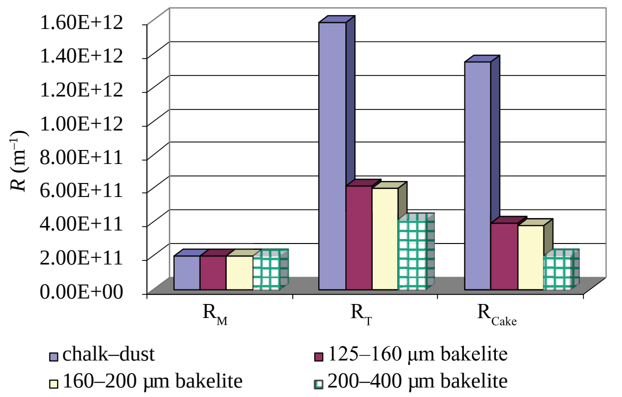

Fig. 7. Comparison of resistance values with different bakelite particle sizes.

References

[1] M.R. Wiesner and P. Aptel, Mass transport and permeate flux and fouling in pressure-driven processes (Chapter 4), in: Water Treatment Membrane Processes, McGraw-Hill, New York, 1996.

[2] M. Kim and A.L. Zydney, Theoretical analysis of particle trajectories and sieving in a two-dimensional cross-flow filtration system, J. Membr. Sci., 281 (2006) 666–675.

[3] K.-J. Lee and R.-M. Wu, Simulation of resistance of cross-flow microfiltration and force analysis on membrane surface, Desalination, 233 (2008) 239–246.

[4] J.M. Frey and P. Schmitz, Particle transport and capture at the membrane surface in cross-flow microfiltration, Chem. Eng. Sci., 55 (2000) 4053–4065.

[5] M. Kim and A.L. Zydney, Particle–particle interactions during normal flow filtration: model simulations, Chem. Eng. Sci., 60 (2005) 4073–4082.

[6] C. Shin, Finite element simulation of deep bedfiltration, Chem. Eng. Sci., 61 (2006) 2324–2329.

[7] L. Fillaudeau and M. Lalande, A practical method to predict steady-state flux and fouling in the crossflow microfiltration of rough beer with 1.40 μm tubular ceramic membranes, Trans IChem, 76 (1998) 217–223.
[8] Z. Wang, Y. Cui, J. Yao, J. Chu and Y. Liang, The influence of various operating conditions on specific cake resistance in the crossflow microfiltration of yeast suspensions, Des. Water Treat., 1 (2009) 237–247.
[9] G. Belfort, R.H. Davis and A.L. Zydney, The behavior of suspensions and macromolecular solutions in cross-flow microfiltration, J. Membr. Sci., 96 (1994) 1–58.
[10] A.A. Makardij, M.M. Farid and X.D. Chen, A simple and effective model for cross-flow microfiltration and ultrafiltration, Can. J. Chem. Eng., 80 (2002) 28–36.
[11] Z. Wanga, J. Chua, W. Wub and J. Yaoa, Study of unsteady-state flux prediction in cross-flow microfiltration, Desalination 238 (2009) 290–301.
[12] R. Rappuoli and D. Unutmaz, Improving membrane filtration processes, Trends Biotechnol., 13 (1995) 129–131.
[13] D. Majumdar and S.P.M.P. William, Chalk dustfall during classroom teaching: particle size distribution and morphological characteristics, Environ. Monit. Assess, 148 (2009) 343–351.
[14] MF/K1 Microfiltration Unit Operating and Maintenance Instructions, Mevatech Kft, Budapest.
[15] A. Román, J. Wang, J. Csanádi, C. Hodúr and Gy. Vatai, Partial demineralization and concentration of acid whey by nanofiltration combined with diafiltration, Desalination, 241 (2009) 288–295.