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ANTI-FOULING MECHANISMS IN ROTATING FILTRATION

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Abstract

Rotating filtration shows considerable advantages over other methods of filtration in preventing membrane fouling. The results of this experimental investigation into the dominant anti-fouling mechanism in rotating filtration suggest that rotational shear is responsible for the majority of the anti-fouling effect, rather than centrifugal sedimentation, axial shear or Taylor vortices. However, the redistribution of azimuthal momentum by Taylor vortices increases the rotational shear. Axial shear and centrifugal sedimentation have small positive impacts on the prevention of fouling.

Introduction

Rotating filtration offers a means of dynamic filtration that minimizes the plugging of the filter pores with particles. The essence of a rotating filter is a Taylor-Couette device consisting of a porous inner cylinder rotating concentrically within an outer non-porous cylinder. Filtrate passes through the inner porous cylinder and is removed through a hollow shaft. Concentrate is removed from the annular gap at the end of the device opposite the suspension entrance. Four mechanisms in rotating filtration could be responsible for reduced membrane fouling: the axial shear due to the annular Poiseuille flow between the two cylinders, the shear due to the circular Couette flow created by the high rotational speed, the centrifugal sedimentation produced by the rotational velocity field, and the Taylor vortices present in the gap, which may wash particles away from the filter surface.

Past research into the effect of the variables present in rotating filtration has been performed only for a sparse set of configurations and parameters. Some of the earliest work in rotating filtration was reported by Hallstrom and Lopez-Leiva [1] for ultrafiltration to produce skim milk. At a throughput of 1.5 l/min, an improvement in filtrate flux from 10 l/hr m^2 to 40 l/hr m^2 was seen as the rotating speed was increased from 0 to 4140 rpm. This increase in filtration flux based on angular velocity has also been seen by other researchers [2,3,4,5,6].

Clearly rotating filtration holds promise for a wide range of separation applications because of the anti-fouling nature of the system. However, there are many design parameters to be considered for the development of a rotating filter for a specific application. Given the large number of parameters, it is difficult to know which combination of values for the parameters will result in optimal filtration for a given situation. Thus, this experimental investigation had two major goals: 1) Identify the most important parameters involved in fouling prevention in rotating microfiltration and quantify their effects; 2) Identify which of the four anti-fouling mechanisms (axial shear, circumferential shear, centrifugal sedimentation, or vortical motion) dominates in rotating filtration.

Methods

A rotating filter approximately 12 cm long and 4.96 cm in diameter rotating in a cylindrical shell with an inner diameter of 5.30 cm was used to examine the effect of the filtration parameters on the degree of fouling. In order to quantify filtration performance and the anti-fouling effect, samples were taken of the inlet suspension feed, the filtrate, the concentrate, and the backflush of the layer of particles that built up on the filter (cake layer) by the end of an experiment. From the concentration and volume of fluid, the total volume of particles entering the test cell, exiting via filtrate, exiting via concentrate and remaining as cake buildup could be calculated. The percentage of total volume of particles entering the device that remained in the cake layer at the end of the experiment, which we call % Cake Layer, was used as a measure of the anti-fouling character for a given set of operating, geometric, and suspension parameters. A high percentage indicates high levels of fouling for a given filtration configuration, while a low percentage indicates little fouling.

The effect of the rate of rotation on the cake layer for a number of angular velocities and filtrate flow conditions is shown in Fig.1. The vertical axis shows the fouling in terms of the percentage of particles that entered the rotating filter test cell that ended up in the cake layer; the horizontal axis is the percentage of the constant 6 ml/s flow rate entering the device that passes through the filter. Clearly, the cake layer has a strong dependence on both the filtrate flow and the rotational speed. At the highest rotational speed, the cake layer is quite small for any filtrate flow. This demonstrates the advantage of rotating filtration in which high rejection rates and recoveries can be achieved in single-pass filtration.

This data can be cross plotted in order to emphasize other aspects of the physics underlying rotating filtration. Fig. 2 shows the dependence of the percentage of particles ending up in the cake layer on the reduced Taylor number for approximately 93% of the inlet flow passing through the filter. Here the speed is expressed as the reduced Taylor number in relation to the critical Taylor number necessary for vortex formation, $\varepsilon=Ta/Ta_c-1$. The percentage of particles ending up in the cake layer decreases as the rotational speed increases. The theoretical critical angular velocity for the appearance of Taylor vortices at $\varepsilon=0$ ($Ta_c=r_i\omega d/\nu=162$ for this radius ratio) is also shown. If the Taylor vortices were the underlying anti-fouling mechanism in rotating filtration, the cake layer percentage would be expected to change dramatically as rotational speed increases from below the transition value to above the transition value.

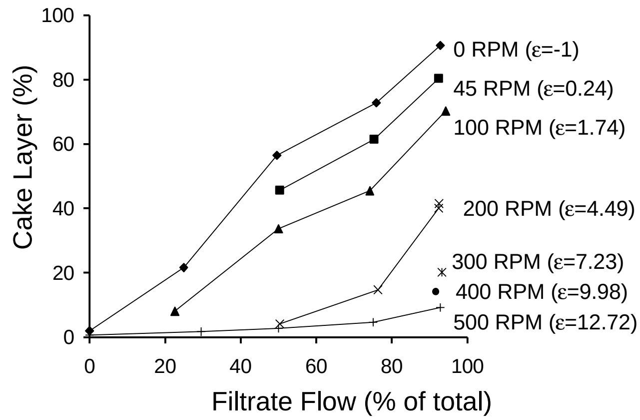

Fig. 1 The effect of rotation and filtrate flow on cake buildup.

However, no sharp change is evident in Fig. 2 within experimental variability. This evidence discounts the importance of Taylor vortices as a significant anti-fouling mechanism. However, the continuous decrease in the cake layer with increasing ε suggests that rotational shear, which increases monotonically with rotational speed, is a significant factor in the anti-fouling character of rotating filtration.

Previous research has suggested that particles in Taylor vortex flow that are denser than the fluid tend to end up on a single limit cycle orbit, irrespective of whether they start at the vortex center or near the cylinder walls [7]. An implication of this idea is that the centrifugal sedimentation, vortical motion, and

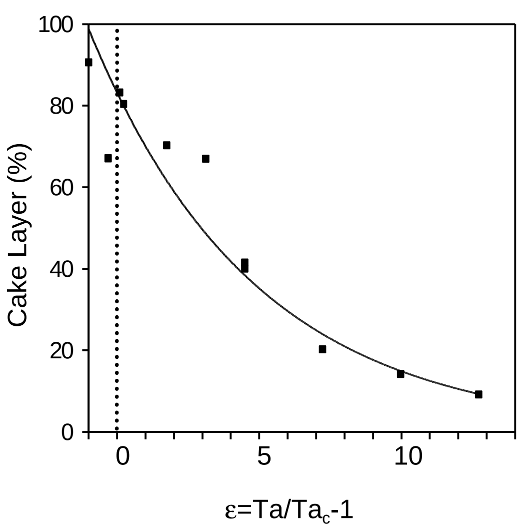

Fig. 2 The dependence of cake layer on rotational speed at 93% inlet suspension flow through the filter. The dotted line is transition to vortical flow at 38.3 rpm.

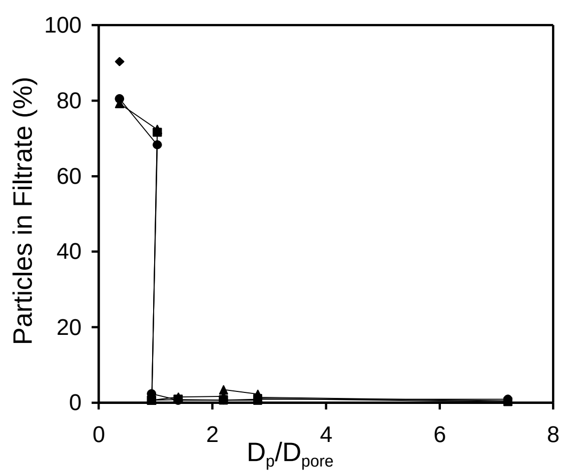

Fig. 3 Particles in the filtrate as a function of ratio of particle diameter to pore diameter. ◆ - 50 RPM, ■ - 100 RPM (ε=1.74), ▲ - 200 RPM (ε=4.49), ●-400 RPM (ε=9.98).

shear related to the fluid flow field are adequate by themselves to prevent fouling, regardless of the filter pore size. To test this hypothesis, trials were done using particles smaller than the pore size in order to challenge the filter. The results shown in Fig. 3 show the percentage of inlet particles passing through the filter with the filtrate as a function of D_p/D_{pore}. A high percentage means very few particles were rejected. Even at high rotation speeds, the pores of the filter must be smaller than the diameter of the particles. The number of particles in the filtrate jumps to an unacceptable value when the ratio of the particle diameter to the pore diameter is less than one.

Conclusions

The results of this study provide insights into the role Taylor vortices play in rotating filtration. The smooth decrease in cake buildup with increasing angular velocity suggests that Taylor vortices serve to increase the shear rate at the surface of the inner cylinder but are not the primary mechanism behind anti-fouling in rotating filtration. In addition, the vortical flow field is not sufficient to prevent particles from passing through a barrier that has pores larger than the particle size.

Acknowledgements

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