CONSIDERATIONS ON OPTIMISATION OF AN INTERMITTENT CROSS-FLOW FILTRATION PROCESS

CONSIDERAȚII PRIVIND OPTIMIZAEA PROCESELOR INTERMITENTE DE FILTRARE PRIN MEMBRANE

GEORGE MOISE

"Lucian Blaga" University of Sibiu

Abstract: *This paper investigates the possibility of finding periodic flow regimes consisting of alternate phases of filtration and membrane cleaning leading to large steady state permeate fluxes, at least when the flux decline is mostly due to the deposited cake layer on the membrane surface.*

Rezumat: *În această lucrare este studiată posibilitatea găsirii periodice a regimurilor de curgere constând în faze alternative de filtrare şi membrane de curăţare ducând la starea de fluxuri permeabile ferme de dimensiuni mari datorate în special stratului depus pe suprafaţa membranei.*

Keywords: *Mineral suspension; Cross-flow filtration; Intermittent micro filtration; Membrane fouling*
Cuvinte cheie*: membrane, suspensii minerale, ultrafiltrare.*

INTRODUCTION

Although membrane fouling is diminished in cross-flow filtration, it remains often sufficient to dramatically decrease the steady state permeate flux. Many techniques have been developed recently to reduce this disadvantage and to enhance micro filtration performance by improving the mass transfer at the membrane surface of the retained species. Recent membrane modules have been designed to include turbulent promoters, inserts to induce mixing, back-pulsing and fluid instabilities. All these techniques have in common the battle against the membrane fouling in the steady or non-steady regime. They aim at increasing back-migration of solute to the bulk flow region and limiting the growth of the particle layer deposited on the membrane.

Many methods have been used to increase turbulence in micro filtration. KNOPS et al. used hollow fiber membranes themselves as turbulence promoters by placing them perpendicular to the feed stream. COSTELLO et al. used a similar technique to that of Knops et al. except that tests were performed on axial flow hollow fiber modules of varying packing density and the presence of a generated transverse flow has been proposed to explain the observed performances enhancement.

Turbulence can be increased by incorporating baffles in a tubular membrane which create a secondary flow, fluid instabilities and local increase of the velocity. A periodically spaced baffle has also been used in combination with a pulsatile flow by MACKAY et al. and WANG et al. BOTH concluded that the baffles and pulsatile flow enhance significantly micro filtration performance.

Pulsatile flow techniques have been performed by MILISIC and BERSILLON and GUPTA et al. and their efficiency is confirmed by many researchers among which Spiazzi et al. who used a rotating perforated disc placed in front of the entering section of a tubular membranes bundle to create temporary velocity increases in the various tubes successively. BELFORT, demonstrated that at high frequencies the maximum velocity increases in amplitude and moves away from the centre line and that the pulsative flow increases substantially the wall shear-rate.

BELFORT and WINZELER and BELFORT have given an interesting review about the use of TAYLOR and DEAN instabilities in boundary layers along curved walls to enhance the cross-flow performance. The vortices produced in the flow result in very high wall shear-rate and the performance improvement has already been tested on the laboratory scale.

Intermittently operated micro filtration has been reported by WHITE and LESECQ and YAZHEN et al. according to different procedures. White and LESECQ used magnesium hydroxide slurries in periodic operation during which filtration and cleaning stages are imposed. Because of the reversible fouling involved with such a suspension, the cleaning phase is realised by stopping the flow. When the flow is resumed, the permeate flux is not entirely recovered and the initial flux of the cycle decreased linearly and a time-averaged steady state was not reached. The time after which the operation is stopped for membrane regeneration is determined according to the procedure used in dead-end filtration optimisation. The results showed that such a procedure could increase the permeate production by quite significant amounts in the case of reversible fouling but the optimisation procedure relied on many hypotheses which are not experimentally confirmed. Yazhen et al. developed a theoretical optimisation of a dead-end filtration with a periodic backwash to remove the cake and restore filtrate flux similarly to that of the filter-press operation. The imperfectly removed internal fouling causes the permeate flux to decrease from cycle to cycle and the required washing time also varies and should be determined for each cycle. This time has been determined neglecting the fact that the backwash flux increases progressively as the internal fouling is removed. In addition, they did not take into account the fact that because of progressive fouling from a cycle to another the membrane should be regenerated when too low a flux is obtained.

MATERIALS AND METHOD

2. THE PROPOSED EXPERIMENTAL SYSTEM

A proposed schematic of the experimental set-up is presented in Fig. 1.

The feed flow to the module is measured by an electromagnetic flow meter and the permeate flux is measured by an electronic scale connected to a microcomputer. The inlet, outlet, and permeate pressures are measured by Validyne transducers via a data acquisition system.

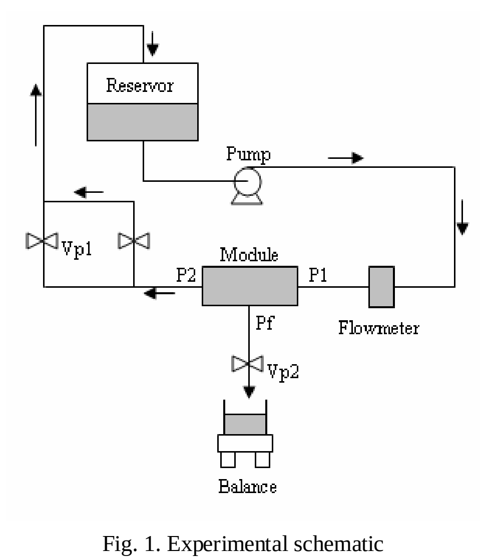

Fig. 1. Experimental schematic

The test bench is also equipped with a timer to program the duration of stepped pressure and velocity changes. This timer acts on pneumatic valves inserted in the circuit in order to switch the retentate and permeate flows from a low resistance circuit to a high resistance one containing a partially closed valve. As shown later the switching of circuits will permit to generate step transmembrane pressure changes at a constant feed velocity or step velocity changes without changing the transmembrane pressure. Such a system is needed since the pump is not truly volumetric and a sudden rise in outlet pressure would decrease the feed velocity.

3. CALCULATION OF SPECIFIC HYDRAULIC ENERGY UNDER UNSTEADY CONDITIONS

Since the filtration tests will be run with changing velocities and pressures, it is necessary to use time-mean parameters in order to compare the various tests. The average transmembrane pressure and permeate fluxes will be defined respectively by

$$\left(\overline{P_{tm}}\right) = \frac{1}{T}\int_0^T P_{tm}(t)dt \qquad (1)$$

$$\overline{J_f} = \frac{1}{T}\int_0^T J_f(t)dt \qquad (2)$$

where T is the period of a full cycle consisting in a filtration phase of duration t_f and a cleaning phase of duration t_c.

$$T = t_f + t_c \qquad (3)$$

The mechanical energy conservation principle indicates that the net energy entering a control volume is equal to the power W consumed by the viscous forces and the variation of the kinetic energy of the mass material in the control volume.

$$-\int_S P_t \vec{V}\cdot\vec{n}dS = \dot{W} + \int_v \frac{1}{2}\frac{\partial\left(\rho V^2\right)}{\partial t}dv \qquad (4)$$

$\vec{V}$ is the velocity vector of the flowing fluid, $\vec{n}$ the external normal to the control volume and S is its outer surface. P_t is the total pressure:

$$P_t = P + \rho g z + 1/2\rho V^2 \qquad (5)$$

The outer surface of the control volume can be considered as the sum of the 2 cross-sections Sc through which the suspension flows and the lateral surface Sp of the membrane and the following equation can be written.

$$\int_S P_t \vec{V}\cdot\vec{n}ds = \int_{2S_c} P_t \vec{V}\cdot\vec{n}ds + \int_{S_p} P_f \vec{V}\cdot\vec{n}ds \qquad (6)$$

where P_f is the permeate pressure.

Since the permeate flow rate is a small fraction of the flow entering the module the velocity V can be regarded to be the same at the inlet and outlet of the module and if gravity effects are neglected (for a horizontal module), we can replace the total pressure by the static pressure P in Eq. (6). Moreover if the permeate pressure P(is atmospheric, it can be taken as zero in Eq. (6) using relative pressures. Thus

$$\int_{S_p} P_f \vec{V}\cdot\vec{n}ds = 0 \qquad (7)$$

In addition, because of the periodicity of the process the variation of the kinetic energy is equal to zero over a period.

$$\int_0^T \int_v \frac{1}{2}\frac{\partial\left(\rho V^2\right)}{\partial t}dvdt \qquad (8)$$

With these considerations, the integral over a period of Eq. (4) gives the hydraulic energy dissipated during a period T in the filtration module as:

$$W = \int_0^T \dot{W}dt = \int_0^T \left(P_1 - P_2\right)Qdt \quad (9)$$

where P, and *P*-, are, respectively, the inlet and outlet pressures of the module. The specific energy consumption in the membrane volume is then calculated as the ratio of the energy consumed and permeate volume produced.

$$\overline{W_{sm}} = \frac{\int_0^T (P_1 - P_2) Q dt}{\int_0^T J_f S_p dt} \qquad (10)$$

Eq. (10) corresponds to the case of a filtration module located inside a circulation loop.

In that case most of the hydraulic energy is supplied by the recirculation pump which yields a much higher flow rate than the feed pump and the main part of the pressure drop in the loop occurs in the filtration module. Thus the numerator of Eq. (10) is close to the hydraulic energy generated by the recirculation pump.

However, in a simple circuit with a simple pump and no recirculation loop, the pump head must be equal to the total pressure which is totally dissipated by the viscous losses in the membrane, the circuit and the valve at the retentate outlet. In that case the specific energy consumption is given by

$$\overline{W_{sc}} = \frac{\int_0^T P_t Q dt}{\int_0^T J_f S_p dt} \qquad (11)$$

Eqs. (10) and (11) will be used to compare the specific energy consumption per m^3 of permeate for an intermittent procedure with alternate filtration and cleaning phases and a conventional steady state operation.

DISCUTIONS

There are three possibilities:

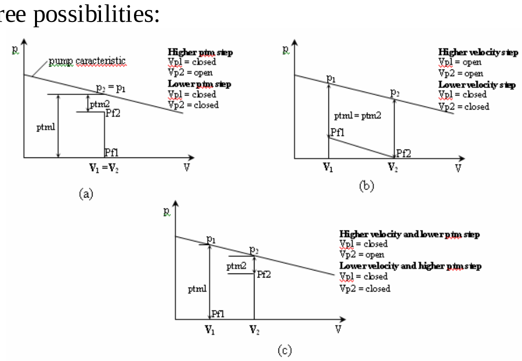

Fig. 2. a. Transmembrane pressure steps at constant velocity; b. Velocity step changes under a constant ptm; c. Simultaneous velocity at ptm step changes.

4.1. Stepped transmembrane pressure changes at constant velocity

To achieve step changes in transmembrane pressure without changing the fluid velocity it is necessary to follow the procedure indicated in Fig. 2.a. The reduction in transmembrane pressure from P_{tml} is achieved by raising the permeate pressure from P_n to P_p by closing the valve V_{p9} and switching to the high resistance permeate circuit. In this operation the retentate pressure is not modified and the fluid velocity is not changed even if the pump is not perfectly volumetric.

A regime of periodic change in transmembrane pressure cannot lead to an increase in the time mean flux in this case as compared to conventional steady cross-flow filtration at the same time pressure. The time mean flux is given by

While the steady flow value will be

$$\overline{J_f} = \frac{\overline{P_{tm}}}{m\left[R_m + R_c\left(\left(P_{tm}\right)_{\max}\right)\right]} \qquad (13)$$

While the steady flow value will be

$$J_{fs} = \frac{\overline{P_{tm}}}{m\left[R_m + R_c\left(\overline{P_{tm}}\right)\right]} \qquad (14)$$

The cake resistance Rc, governed by the maximum pressure will be higher than the corresponding steady flow resistance at a pressure equal to the time average pressure of the intermittent operation and Jt will be less than Jfs.

4.2. Velocity step changes at constant P_{tm}

The procedure for achieving velocity step changes without change in P_{tm} is indicated in Fig. 2.b. The velocity is raised from V_t to V, by closing the valve V_p| and switching the retentate flow from a partially clamped circuit to a low resistance one but since the mean pressure of the solution is lowered from P_J to P_2 as a result of the lower resistance, the permeate pressure must be lowered by the same amount from P_n to P_{f2} to conserve the transmembrane pressure.

4.3. Simultaneous pressure and velocity step changes

As mentioned earlier membrane cleaning may be more effective if the transmembrane pressure is lowered at the same time as the velocity is increased. The procedure for achieving such simultaneous pres-

sure and velocity changes is similar to that for velocity changes and is illustrated in Fig. 2.c. The difference is that the valve V_{p2} is now closed during the high velocity phase in order to raise the permeate pressure and obtain a reduced transmembrane pressure during this phase.

RESULTS AND DISCUSSION

This work confirms that, in the case of superficial membrane fouling caused by particles larger than the pores of the membrane, a procedure of intermittent filtration separated by short phases of low pressure and high velocity can sustain a self cleaning regime. For the cleaning mechanism to be effective, a critical stress must be attained at the cake surface so that the top layer gets eroded and the particles diffuse back into the bulk solution.

This method can be regarded as a low frequency alternative to pulsatile flow technique developed by Jaffrin et al. which produces periodic bursts of velocity and pressure along the membrane at frequencies of about 1 Hz. It is probably easier to extrapolate at large membrane areas than the pulsatile technique which requires a stroke volume of the order of the membrane inner volume.

The energy calculations confirm that, in conventional steady flow filtration, a large part of the hydraulic energy produced by the pump is wasted by the high kinetic energy required to limit the cake growth. The intermittent filtration technique that we propose requires in theory much less hydraulic energy to limit the cake growth.

However, our calculations based on experimental measurements of pressure and velocities may not be representative of the actual electrical energy consumed by the pumps.

The reason is due to the large change in velocities required. If the reduction of velocity is achieved by rerouting the flow in a bypass, not much energy will be saved at low velocity. The same is true if the low velocity is obtained by increasing the load on the pump through a partially closed valve. Obviously clever technical solutions must be found in order that the theoretical energy savings shown in Table 1 actually correspond to similar savings in electrical energy supplied to the pump. Another difficulty lies in the fact that the high velocities must be associated with lower transmembrane pressure while actually the pressure drop increases.

It would be hazardous to extrapolate these data to the case of biotechnological fluids containing colloidal particles. In that case the fouling phenomenon is more complex and not exclusively on membrane surface. Thus the permeate enhancement obtained by this method will be less.

6. List of symbols

J_f	permeate flux	V	fluid velocity
P_{lm}	membrane average transmembrane pressure	T	period
P_t	total pressure	W	energy consumed during a period
$P_($	permeate pressure	W_{sc}	specific energy consumed in the whole circuit volume
Q	suspension flow rate	W_{sm}	specific energy consumed in the membrane volume
R_c	cake resistance	/x	viscosity
R_m	membrane resistance	p	fluid density
S_c	tubular membrane cross-section		
S_p	membrane lateral surface		

LITERATURE

1. G. BELFORT, R.H. DAVIS AND A.L. ZYDNEY. The behavior of suspensions and macromolecular solutions in crossflow filtration, J. Membrane Sci., 96 (1994) 1-58.
2. F.N.M. KNOPS, H. FUTSELAAR AND I.G. RACZ, The transversal flow micro filtration module. Theory, design, realization and experiments, J. Membrane Sci., 73 (1972) 153-161.
3. M.J. COSTELLO, A.G. FANE, P.A. HOGAN AND R.W. SCHOFIELD, The effect of shell side hydrodynamics on the performance of axial flow hollow fibre modules, J. Membrane Sci., 80 (1993) 1-11.
4. B.B. GUPTA, D. WU, R.W. FIELD AND J.A. HOWELL, Permeate flux enhancement using a baffle in micro filtration with mineral membrane, in E.F. Vassaut (Ed.), Separation Technology, Vol. 11, Elsevier, Amsterdam, 1994, pp. 559-565.
5. M.E. MACKAY, M.R. MACKLEY AND Y. WANG. Oscillatory flow within tubes containing wall or central baffles, Trans. Inst. Chem. Eng., 69A (1991) 506-513.
6. Y. WANG. J.A. HOWELL, R.W. FIELD AND D. WU, Simulation of cross-flow filtration for baffled tubular channels and pulsatile flow. J. Membrane Sci., 95 (1994) 243-258.
7. V. MILISIC AND J.L. BERSILLON, Anti-fouling techniques in crossflow-microfiltration, Filtration Sep., 23 (1986) 347-349.
8. B.B. GUPTA, P. BLANPAIN AND M.Y. JAFFRIN, Permeate flux enhancement by pressure and flow pulsations in micro filtration with mineral membranes, J. Membrane Sci.. 72 (1992) 267-275.
9. E. SPIAZZI, H. BOLLEAU, J. LENOIR AND A. GRANGEON. A new generator of unsteady-state flow regime in tubular membranes as an anti-fouling technique, hydrodynamic approach. J. Membrane Sci., 80 (1993) 49-57.
10. G. BELFORT, Fluid mechanics in membrane filtration: recent developments, J. Membrane Sci.. 40 (1989) 123-147.
11. H.B. WINZELER AND G. BELFORT, Enhanced performance for pressure-driven membrane processes: the argument for fluid instabilities. J. Membrane Sci., 80 (1993) 35-47.
12. D.A. WHITE AND P. LESECQ. Optimisation of intermittently operated micro filtration processes, Chem. Eng. J., 52 (1993) 73-77.
13. Y. XU, J. DODDS, D. LECLERC, Optimization of a discontinuous micro filtration backwash process. Chem. Eng. J., 57 (1995) 247-251.
14. C.S. VASSILIEFF, I.G. MOMTCHILOVA AND R.A. KRUSTEV, Cross-flow micro filtration of Kaolinite-in-watcr dispersions. Colloids Surf., 92 (1994) 231-247.