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<http://dx.doi.org/10.2166/ws.2015.158>

PUBLISHER

IWA Publishing

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

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Shamsuddin, Norazanita, Chengcheng Cao, Victor Starov, and Diganta Bhusan Das. 2015. "A Comparative Study Between Stirred Dead End and Circular Flow in Microfiltration of China Clay Suspension". figshare.
<https://hdl.handle.net/2134/19479>.

A comparative study between stirred dead end and circular flow in microfiltration of china clay suspension

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Abstract

A well-defined comparative study between stirred dead end and circular crossflow for microfiltration of china clay suspension has been undertaken. The comparisons have been made with respect to convective mass transfer coefficients, permeation and rejection rates, and energy consumption. Similar operating and hydrodynamic conditions were implemented for the comparison. According to our experimental data circular crossflow module was proven to perform better as compared with the stirred dead end system due to the higher mass transfer coefficients, higher permeation rates and lower energy consumption. The mass transfer coefficients observed are comparable to previously found in vortex flow filtration and dead end flow filtration. The presence of Dean vortices in circular crossflow module promotes flow instabilities in the curved channel flow path which reduce concentration polarization effect during the filtration process. The concentration polarization effect however deteriorated due to solute build up (high solute concentration at the membrane surface) and decrease of the shear stress, i.e., the particle lift forces on the membrane surface. This resulted in deposition of particles on the membrane surface. In terms of energy consumption, for the same energy cost the limiting flux reached in circular crossflow is found higher than in stirred dead end unit.

Keywords: *Circular crossflow – Stirred dead end – Shear stress – Dean vortices – Microfiltration – Mass transfer coefficient*

1. Introduction

Microfiltration (MF) is regarded as one of the oldest separation techniques among the pressure-driven membrane separation processes (Strathmann et al., 2011). Both MF and ultrafiltration (UF) membranes have been used extensively for the removal of particles, turbidity and microorganisms for water treatment (Gray et al., 2011; Shamsuddin et al., 2014). However, membrane fouling is a major impediment to membrane efficiency and it results in the reduction of membrane performance (Kochkodan et al., 2014; Guo et al., 2012; Gao et al., 2011). Despite the vast efforts to reduce the effect of membrane fouling by improving membrane properties, optimizing operating conditions and pre-treatment of feed water, fouling is unavoidable (Costa et al., 2006). Improved hydrodynamic conditions such as manipulating shear rates on membrane

surfaces, improved design of the membrane modules, and induced flow instabilities are other useful methods in overcoming membrane fouling and concentration polarization (Jaffrin, 2012).

Researchers have discussed various ways to induce these flow instabilities such as Taylor (Park et al., 1994; Belfort et al., 1993; Kroner and Nissinen, 1988) and Dean vortices (Kaur and Agarwal, 2002; Manno et al., 1998; Nunge and Adams, 1971; Srinivasan and Tien, 1971). Taylor vortices, which are resulted from rotating annular filter, was found to be one the most succesful techniques in reducing concentration polarization effects and membrane fouling. Both vortices have similarities in principles and use centrifugal forces to give rise to secondary flows which disrupt solute build-up on membrane surfaces, thus reducing concentration polarization and increasing permeation rates. However, Taylor vortices require substantially more energy than stationary Dean vortices. Hence, Taylor vortices have limited potential for upscaling as compared to Dean vortices. Experimental investigations undertaken by Belfort and his co-workers (1993-1997) proved that Dean vortices effectively improve membrane filtration performances using curved channel modules. Kaur and Agarwal (2002) was the first to the best of our knowledge, who studied the effects of Dean vortices on filtration performance involving ultrafiltration of protein suspensions in circular thin flow channel module. They have experimentally calculated the mass transfer coefficients which were found to be higher than classical filtration models by a factor 7-10.

The objective of this paper is to study the effects of Dean vortices on reducing concentration polarization and membrane fouling, and an increase of permeation fluxes in the case of MF of china clay suspensions through the study of hydrodynamics. While a significant amount of research has been done for reverse osmosis (RO) and UF which were widely used for desalination and removal of natural organic matter, MF for china clay particles draws less attention. Also, little research has been done for the influence of membrane configurations on the filtration performance. Thus, in this study, a comparison between circular crossflow and stirred dead end flow is attempted. Hydrodynamic condition such as shear stress on membrane wall which determined the mass transfer coefficients of particles needs to be investigated as Becht et al. (2008) explained it is essential to define hydrodynamic conditions in much detail without leaving out the importance similar operating conditions during comparison experiments. Hence, the aim of this paper is to investigate the hydrodynamic conditions of the two set-ups, i.e. circular crossflow and stirred dead end flow using china clay suspension as contaminant, and MF membranes for filtration processes as detailed below.

2. Experimental Procedure

2.1. Materials

Microfiltration experiments were performed with mixed cellulose ester membrane (GSWP09000) consisting of cellulose acetate and cellulose nitrate which has an average pore size of 0.22 μm

(Merck Millipore, Darmstadt, Germany). According to the manufacturer, the membranes are hydrophilic with thickness and porosity of 150 μm and 75%, respectively. A view of the clean membrane sample pictured using scanning electron microscope (SEM) is shown in Figure 1 (a). The particle size distribution of clay particles (Sigma-Aldrich, Dorset, UK) was evaluated using Malvern-Sizer laser light scattering instrument (Malvern Instruments, Malvern, UK) and the result is shown in Figure 1 (b).

Figure 1 (a) membrane sample of 0.22 μm mixed cellulose ester, (b) Particle size distribution of clay particles.

2.2. Preparation of sample filtration

Prior to filtration experiments, the membrane was soaked in deionized water for 1 hour with water changing every 20 minutes in order to remove any wetting agents. Measurement of pure water fluxes for each clean membrane was carried out. The ionic strength was adjusted to 0.01M (0.585 g/l) by adding sodium chloride (NaCl), purchased from Sigma-Aldrich (Dorset, UK), into the china clay suspensions. In order to produce a homogeneous mixture the suspension was placed prior to the experiments in an ultrasonic water bath for approx. 30 minutes at temperature of $22 \pm 2^\circ\text{C}$. The pH of the china clay suspensions was adjusted to the selected pH values by adding various amount of hydrochloric acid (HCl) or sodium hydroxide (NaOH), which were bought from Sigma-Aldrich (Dorset, UK) into the suspensions. The turbidity of the prepared suspensions was measured by a turbidity meter (model 20000; HF Scientific, Fort Myers, USA).

Figure 2 Schematic diagrams of filtration apparatus with (a) stirred dead end module, (b) circular crossflow module, and (c) side views of circular crossflow cell and stirred dead end flow respectively.

2.3. Membrane filtration apparatus

For the comparison of experiments two different configurations were used. Circular crossflow module manufactured by Amicon (Massachusetts, USA) and stirred dead end apparatus (model XFUF07601) purchased from Merck Millipore (Darmstadt, Germany).

A schematic of the experimental set up is shown in Figure 2. The stirred dead end system (Figure 2 (a) and (c)) has a fixed volume of 300 ml. The cell has an effective filtration surface area of 40 cm² with diameter of 76 mm. The feed reservoir was agitated by a flat blade paddle impeller (65 mm diameter and 9 mm height). Prior to filtration experiments the feed suspension was added into the feed reservoir. The membrane was placed at the bottom of the filtration cell while the pressure from nitrogen cylinder was monitored by a pressure gauge and controlled by a pressure regulator (model 8286; Porter Instrument Co., Hatfield, USA). The speed of the flat blade paddle impeller was measured using a digital tachometer (Shenzhen Ever Good Electronic Co Ltd, Shenzhen, China).

Figure 2 (b) – (c) shows circular crossflow module with inside view of the filtration cell. The module has a feed volume of 600 ml and 40 cm² effective filtration surface areas. Both the feed and the retentate were recycled back into the feed reservoir at room temperature in order to maintain a constant suspension concentration throughout the filtration experiment. Figure 2 (c) shows a flow pattern of the suspension in a circular channel over the membrane surface. There were three spirals with radii from 1 cm to 4.1 cm, with channel spacing of approximately 1 cm. The spiral channel has the following specs: length (760 mm), width (9.5 mm) and height (0.38 mm) according to the manufacturer. The feed reservoir was pressurized by nitrogen which was adjusted to a predetermined pressure using manually operated valves. Pressure indicator was used to monitor pressure inside the feed vessel. Calibration of pressure gauges was conducted for both modules by validating the gauges with precise gauge at changing pressures values. A new clean membrane was used and pre-treated for every new set of experiment. All experiments were carried out at room temperature (22°C ± 2°C). Permeate collection was made at 1 min intervals.

3. Theory

In the circular flow module the difference in pressures between internal and external walls of the circular channel flow gives rise to secondary flows known as Dean vortices. This phenomenon was shown to exist in such module above a critical Reynolds number (Kaur and Agarwal, 2002). Equation (1) can be used to calculate Dean number in the curved channel (Dean, 1928):

$$De = Re_{CF} \sqrt{\frac{d_i}{d_c}}, \quad (1)$$

where Re_{CF} is the Re number above critical Re (approx. 33-45), which was found experimentally by Brewster et al. (1959); d_i is the equivalent hydraulic diameter calculated to be 0.0745 cm; and

148 d_c is the diameter of curvature of the channel path has been calculated to be 4.51 cm.

149 As mentioned earlier, it is essential to have similar operating conditions for comparison but one
150 must not leave out the importance of hydrodynamic conditions in order to satisfy the purpose of
151 comparison. Therefore the calculation of shear stress in circular flow system was made
152 according to Becht et al. (2008), i.e., by solving the force balance across the membrane:

$$153 \quad \tau_{CF} = \frac{\Delta P d_i}{4L}, \quad (2)$$

154 where ΔP is the transmembrane pressure, and $L = 760$ mm is the length of the membrane
155 channel. A predetermined filtration pressure of 0.1 bar with cross flow velocity of 1.156 m/s
156 resulted a flow profile pattern which corresponds to the Reynolds number of 867 and a shear
157 stress approx. 1.27 Pa.

158 However, similar calculation for the case of stirred dead end filtration is not straight forward.
159 According to Kosvintev et al. (2005) the filtration cell has to be divided into two regions i.e. inner
160 region and outer region. At the critical radius of the flat blade paddle impeller, the shear stress is
161 the highest but then decreases as it reaches the outer region. Therefore, in order to calculate the
162 shear stress across the whole membrane, an average value of both the inner and outer regions
163 should be calculated. Kosvintsev et al. (2005) developed the following correlation to find the
164 critical radius:

$$165 \quad r_c = \frac{D_i}{2} 1.23 \left(0.57 + 0.35 \frac{D_i}{D_t} \right) \times \left(\frac{h}{D_t} \right)^{0.036} n_b^{0.116} \frac{Re_i}{1000 + 1.43 Re_i}, \quad (3)$$

166 where D_i is the diameter of flat blade paddle impeller, D_t is the diameter of the filtration cell, h is
167 the height of the flat blade paddle impeller, Re_i is the Reynolds number for the flat blade paddle
168 impeller, and n_b is the number of flat blade paddle impeller used.

169 The Reynolds number for both modules i.e. circular crossflow and stirred dead end can be
170 calculated using Equations (4) and (5) respectively:

$$171 \quad Re_{CF} = \frac{\rho u d_i}{\mu}, \quad (4)$$

$$172 \quad Re_{DE} = \frac{\rho \omega r_t^2}{\mu}, \quad (5)$$

173 where μ is the dynamic viscosity of the fluid, ρ is the density of the fluid, r_t is the radius of the
174 filtration cell, and ω is the angular velocity. Equation (5) was also used to calculate Re_i .

175 Shear stresses on the inner and outer regions are given by Equations (6) and (7) respectively:

$$176 \quad \tau_i = 0.825 \mu \omega r \frac{1}{\delta}; \quad \text{for } r < r_c, \quad (6)$$

$$\tau_o = 0.825\mu\omega r_c \left(\frac{r_c}{r}\right)^{0.6} \frac{1}{\delta}; \quad \text{for } r > r_c \quad (7)$$

$$\text{where } \delta \text{ is the momentum boundary layer } \left(\delta = \sqrt{\frac{\mu}{\rho\omega}}\right).$$

The stirred dead end module has a critical radius of 2.37 cm. In order for the system to achieve a similar shear stress as in the circular flow module, the flat blade paddle impeller requires rotation speed of 145 rpm, which equals to the shear stress of 1.27 Pa.

Cussler (2009) defined mass transfer coefficient as resistance to diffusion rate constant for solute movement in boundary layer at the solid and liquid interface. Mass transfer coefficient was calculated according to the concentration polarization model proposed by Zydney and Colton (1986), Colton et al. (1975), and Blatt et al. (1970). Diffusion coefficient (D) is defined as the ratio of molar flux and the driving force, and determined by the Stokes-Einstein (Einstein, 1905):

$$D = \frac{k_B T}{6\pi\mu r_s}, \quad (8)$$

where k_B is Boltzmann constant ($1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$), T is the operating temperature in Kelvin, and r_s is the average radius of china clay particles. Hence, the diffusion coefficient D according to Equation 8 was found to be $2.755 \times 10^{-14} \text{ m}^2/\text{s}$.

The theory for calculation the mass transfer coefficient for the circular crossflow was explained elsewhere (see e.g., Kaur and Agarwal, 2002). The following Sherwood correlation was developed from our experimental results to describe the mass transfer coefficient for circular crossflow module i.e. mass transfer of solutes from membrane interface into the bulk phases, k_m :

$$Sh = 2.61De^{1.02}Sc^{0.33}, \quad (9)$$

where Sc is the Schmidt number which is the ratio of viscous diffusion rate and molecular diffusion rate ($Sc = \frac{\mu}{\rho D}$).

The mass transfer coefficient for the stirred dead end system can be obtained from the typical mass transfer correlations. The mass transfer coefficient, k_n , in the stirred dead end cell was obtained from the following Sherwood, Sh , correlation (Mehta and Zydney, 2006):

$$\left(\frac{k_n r_t}{D}\right) = Sh = 0.27Re_d^{0.567}Sc^{0.33}. \quad (10)$$

4. Results and Discussions

4.1. Comparison of circular crossflow module and stirred dead end module

4.1.1. Filtration performance

Pure water fluxes of six clean cellulose ester membrane samples were measured for the investigation of hydraulic membrane resistance under constant transmembrane pressure of 0.05bar for both circular crossflow system and stirred dead end system. Figure 3 illustrates total hydraulic resistances of membranes for both modules. The flux can be related to the total hydraulic resistance according to Darcy's law. Pure water fluxes measurement in circular crossflow system (ranges between 550-650 l/hr.m²) are much higher than that in stirred dead end system of approx. 120 l/hr.m². Hydraulic resistance has an inversely proportional relationship with flux according to the following equation:

$$J = \frac{\Delta P}{\mu R_{tot}}, \quad (11)$$

where J is the permeate flux(m³/m²s), ΔP is transmembrane pressure (Pa), μ is the dynamic viscosity (Pa.s), and R_{tot} is the total hydraulic resistance (m⁻¹).

The differences in total hydraulic resistances for both modules are shown in Figure 3. Total hydraulic resistance in the circular flow module are much lower than in the stirred dead end. This is attributed to the effect of Dean vortices in the circular crossflow module. The flow pattern changes from typical laminar flow into an unstable laminar flow called Dean vortices when a fluid flows in the curved channel path at Reynolds number above the critical Reynolds number. As a result of flow instabilities the resistance becomes lower according to Winzeler and Belfort (1999). The absence of such flow instabilities in stirred dead end results in much higher hydraulic resistance.

Figure 3 Total hydraulic resistances provided by membrane samples for circular crossflow module and stirred dead end module.

All filtration experiments were carried out with suspension concentration (0.4 g/l), ionic strength (0.01M) and the filtration pressures (0.1bar and 0.05 bar, respectively) for direct comparison between the circular flow module and stirred dead end module. The flow profile of circular flow is laminar which corresponds to the Reynolds number of 867 according to Equation (4). The cross-flow velocity has been calculated as 1.156 m/s. Reynolds number of the stirred dead end system was found 21,352 (turbulent flow) using Equation (5). Instead of keeping the Reynolds number uniform for both systems, the shear stresses on top of the membranes were made equal in order to maintain the entire operating conditions consistent for comparison. Equations (2) – (7) were used to calculate the shear stresses for both modules which were equal to 1.27 Pa.

Limiting flux for circular crossflow is six times greater than for stirred dead end (Figure 4). After 25 minutes the flux varied within $\pm 5\%$, hence, a steady state value was reached in the case of circular crossflow module. A steady state flux was also reached in the case for stirred dead end module, however, much faster (less than in 10 minutes) and much lower value (Figure 4). This is attributed to the presence of Dean vortices effect in circular crossflow, which depolarized solute build-up near the membrane interface: due to the higher wall shear stress particle were removed from the membrane surface. This resulted in an intensive mixing between the boundary layer and the bulk phase (Bubolz et al., 2002). The formation of Dean vortices in circular flow module slowed down formation of the steady state accumulation of solutes on membrane surface in the early stage of the filtration process. Hence, the presence of Dean vortices results in improvement of mass transfer of solute from the membrane surface into the bulk solution.

Figure 4 Permeate fluxes for circular crossflow module and stirred dead end module.

4.1.2. Mass transfer coefficients

The mass transfer coefficients calculated for circular crossflow system are in the range between 1.19×10^{-6} m/s and 3.66×10^{-6} m/s calculated according to Equation (9). The mass transfer coefficients for stirred dead end system are calculated according to Equation (10) and are found in the range between 1.12×10^{-7} m/s and 4.31×10^{-8} m/s. According to Muller et al. (2003) for dead end filtration typical mass transfer coefficients were found about 5×10^{-8} m/s, whereas for cross flow filtration 1×10^{-6} m/s to 5×10^{-6} m/s, and for vortex flow filtration 0.5×10^{-5} m/s to 4×10^{-5} m/s. Hence, from our results the mass transfer coefficients for circular crossflow were comparable with those obtained for vortex flow filtration. We concluded that it was due to the presence of Dean vortices in the circular crossflow that resulted in improved mass transfer coefficient. Circular crossflow module showed better performance than stirred dead end module as shown in Figures 3 and 4 at similar operating and hydrodynamic conditions. In stirred dead end module the absence of such vortices led to a rapid build-up of solutes on membrane surface thus concentration polarisation effect took place. Although there was a stirrer to minimize the solute build-up it still could not reduce the concentration polarization effect as filtration process progressed.

270 Table 1 Observed rejection coefficient for circular crossflow and stirred dead end modules.

Configuration	Permeate turbidity (NTU)	Clay concentration in permeate (g/l)	Observed Rejection coefficient
Circular crossflow	0.35±0.04	0.001302±0.05	0.996744±0. 06
Stirred dead end	0.91±0.06	0.003317±0.05	0.991708±0. 03

271
272 Observed rejection coefficients were found to be close to one according to Table 1. The true or
273 actual rejection percentage can be calculated using the following formula using the film model
274 for concentration polarization (Blatt et al., 1970):

$$275 \quad R_{tr} = \frac{R_{obs}}{(1-R_{obs}/\exp(J/k)+R_{obs})} \cdot \quad (12)$$

276 As filtration process progressed, the observed rejection coefficients changes very slightly and lie
277 within 3% to 6% variation as shown in Table 1. The true rejection percentages were calculated
278 for both modules which were close to one. High solute concentration near the membrane
279 surface led to the diffusion of the solute component in the opposite direction i.e. to the bulk.
280 Therefore, concentration polarization did take place on membrane surface but more severe in
281 the case for stirred dead end module as seen in Figure 4. The reason why such phenomenon
282 took place in circular crossflow module was because of lower wall shear stress of 1.27 Pa and
283 concentration of solute used was high (0.4 g/l). This resulted in a decreasing influence of effect
284 of Dean vortices as filtration progressed because due to rapid solute build up and shear stress
285 decreased the particle lift forces thus resulting in a deposition of solutes on the membrane
286 surface. Therefore, it would be very important to search for the optimum operating and
287 hydrodynamic conditions, i.e. higher wall shear stress (high operating pressure) and lower solute
288 concentration might be desirable.

Figure 5 Effect of suspension concentrations of 0.2 g/l, 0.4 g/l, and 0.6 g/l on permeate flux decline for circular crossflow module.

We investigated the influence of concentration of china clay particles on the flux decline in the circular crossflow system and the results are shown in Figure 5. The cross flow velocities and filtration pressure are kept the same for all the experiments. Generally, it can be seen from Figure 5 that the permeate flux decreases with the increasing solids concentration of the feed suspension. This observation is consistent with that of Hwang and Sz's (2011).

Scanning electron microscope (SEM) images of top surface of the membranes are obtained at solids concentration of 0.2 g/l and 0.6 g/l in order to investigate the situation of membrane fouling after the microfiltration process (Figure 6). At higher concentration, there is a tendency for more china clay particles accumulated on the surface of the membrane which leads to the formation of a cake layer. As seen from Figure 6, the higher the suspension concentration, the thicker the cake layer is since china clay particles deposited on the membrane surface at fixed suspension volume. The increasing thickness of the cake layer contributes to the resistance which confirms the observation mentioned above.

Figure 6 Scanning electron microscope (SEM) images of membrane surfaces after filtration process at different concentrations: (a) 0.2 g/l, and (b) 0.6 g/l.

The typical impact of the filtration pressure on the flux decline is shown in Figure 7, which was consistent with Hwang and Sz's (2011). However, the permeate fluxes also decrease more rapidly with increasing filtration pressure. This phenomenon is very significant with the microfiltration of large particles like the china clay particles used in the experiments (Tarleton and Wakeman, 1994). Figure 7 shows that the permeate fluxes are directly proportional to the filtration pressure.

Figure 7 Effect of filtration pressures of 0.01 bar, 0.05 bar and 0.1 bar on permeate flux decline. Suspension concentration is 0.4 g/l.

In order to further verify the trends in terms of flux decline (Figure 7) caused by the change in the filtration pressure, SEM images are collected for measuring the thickness of the cellulose ester membrane samples after the filtration process. The thickness of the membrane is 150 μm as indicated by the manufacturer. As seen from Figure 8 different filtration pressures did not have significant influence on the thickness of the membranes in the investigated range of transmembrane pressures. The thicknesses are the same (about 150 μm after the experiment) which indicates that the membrane characterisations stay constant for each membrane employed.

Figure 8 Scanning electron microscope images of the cross section of each membrane after filtration process at different filtration pressures: (a) 0.01bar, (b) 0.05bar, and (c) 0.1bar.

The decreased influence of Dean vortices was observed as filtration progressed due to rapid solute build up and shear stress decreased the particle lift forces thus resulting in deposition of solutes on membrane surface. Therefore, it would be very important to search for optimum operating and hydrodynamic conditions, i.e. higher wall shear stress (high operating pressure, greater than 0.1 bar) and dilute solute concentration might be desirable (less than 0.2 g/l), in order to have maximum effect of Dean vortices.

4.1.3. Energy consumption

Energy consumption is an important aspect to consider the feasibility of an industrial application. The energy consumption for both systems were calculated and compared at similar operating conditions. According to Manno et al. (1998), the energy dissipated per unit volume of permeate, E can be calculated using the following formula:

$$E = [Q/Q_p \Delta P_{IO} + \Delta P]/3.6 \times 10^6, \quad (13)$$

where Q is the feed flow rate, Q_p is the permeate flow rate, ΔP_{IO} is the pressure difference between the inlet and outlet, and ΔP is the transmembrane pressure.

Figure 9 Ratio of limiting flux in circular crossflow to stirred dead end as a function of dissipated energy.

Figure 9 shows the limiting ratio (circular crossflow to stirred dead end) as a function of energy dissipated. For the same energy rate, the limiting flux reached in circular crossflow is always higher than stirred dead end. Observation on energy consumption by any modules with Dean vortices effects was also made by Moulin et al. (1999) and Manno et al. (1998). They concluded that the presence of Dean secondary flow even at fixed amount energy dissipated would result in more permeation fluxes compared to other conventional modules. With regard to the energy calculations both set-ups i.e. circular crossflow and stirred dead end operated at quite low pressures (0.1 bar and below) for the filtration experiments, hence, it was predicted that the amount of energy dissipated would be low as well. Also, the time required for the filtration

experiment to complete at filtration pressure of 0.1 bar was less than 1 hour. Also, the system is scalable and the scalability of this analysis would be presented elsewhere.

5. Conclusions

Comparative study between stirred dead end and circular crossflow in microfiltration of china clay suspension was investigated. Comparison was made with respect to convective mass transfer coefficients, permeation and rejection rates, and energy consumption. Similar operating and hydrodynamic conditions were implemented. From our experimental data circular crossflow module was proven to perform better when compared to the stirred dead end system due to the higher mass transfer coefficients, higher permeation rates with lower energy consumption. The mass transfers gathered are comparable to studies previously done in vortex flow filtration and dead end flow filtration. The presence of Dean vortices in circular crossflow module promotes flow instabilities in the curved channel flow path which reduced concentration polarization effect during the filtration process. For the same energy cost, the limiting flux reached in circular crossflow is always higher than stirred dead end. Hence, it is proven that energy consumed was less for circular crossflow module than for stirred dead end module with higher permeation rates. From the study of hydrodynamics of both set-ups, the mass transfer coefficients of particles could be determined. Hence, it is proven to have significant advances in the practical and theoretical aspects of water science and technology as presented elsewhere by the authors.

6. Acknowledgements

The authors would like to thank Brunei Government for the PhD studentship granted to Norazanita Shamsuddin at Loughborough University.

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