Cross-Flow Microfiltration Characteristics of *Streptococcus bovis* in the Lactic Acid Fermentation Broth Produced by Fresh Cassava Roots

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The cross-flow filtration characteristics of bacterial cells (*S. bovis*) obtained from a lactic acid fermentation broth of fresh cassava roots have been investigated in terms of specific cake resistance. The amount of particles accumulated on the membrane surface was evaluated using a cake filtration model. The effects of the operating conditions (transmembrane pressure, cross-flow velocity and cell concentration) on permeate flux, cake resistance and specific cake resistance were studied. The cake properties in cross-flow filtration were then compared to those in dead-end filtration. The specific cake resistance in the cross-flow filtration shows a higher value than in the dead-end filtration for almost the same cake compressibilities of about 1.0. The specific cake resistance increases with increasing cross-flow velocity and decreases with increasing cell concentration until reaching a concentration at which the specific cake resistance hardly changes. The increasing ratio of the specific cake resistance in the cross-flow filtration over the dead-end filtration is found to be independent of the transmembrane pressure and cell concentration.

Introduction

The use of cross-flow filtration integrated with fermentation for the continuous production of lactic acid has been widely studied. This process, called a membrane bioreactor system, allows for cell recycling in order to achieve high cell concentrations. High cell concentrations in a system increase productivity. The efficiency of this membrane bioreactor for the enhancement of lactic acid productivity has been successfully demonstrated in a number of previous studies (Kwon *et al.*, 2001; Xu *et al.*, 2006; Wee and Ryu, 2009).

A study of membrane separation was first needed to understand the separation characteristics of bacterial cells during the continuous operation of membranes in a cross-flow mode. An understanding of permeate flux and specific cake resistance is needed to define the performance of cross-flow filtration. The cross-flow filtration method is simply characterized by a rapid decline in the filtrate flux from the initial, clean membrane value to a steady state or pseudo-steady state value. In most situations, the steady state flux is found to increase with increasing transmembrane pressure and cross-flow velocity and to decrease with increasing concentration and membrane resistance (McCarthy *et al.*, 2002). Various permeate flux decline models have been proposed to describe the effects of the operating conditions on membrane performance (Carrere *et al.*, 2001; Juang *et al.*, 2008).

However, the specific cake resistance cannot be tracked during filtration because the cake mass per unit area cannot be easily measured, particularly for the monolith-type membranes used in cross-flow filtrations. Despite these experimental difficulties, there are several studies in the literature that provide direct information about cake formation in cross-flow filtration. Tanaka *et al.* (1996) used a thin-channel-type module with a flat membrane to conduct cross-flow filtration in which they could simply weigh the amount of cake formed on the membrane surface. Vyas *et al.* (2000) removed the cake from the tubular membranes by pushing a cleaning rod through the flow channel. However, none of these methods can be applied to the dynamics of cake build-up.

To overcome the difficulties associated with the measurement of specific cake resistance, Furukawa *et al.* (2008) used the more acceptable hydrodynamic model approach. The specific cake resistance of the cross-flow filtration was evaluated using a cake filtration model by assuming that the accumulation of particles on the membrane was proportional to the particle concentration and the difference between the permeate flux and the hydraulic lift velocity of the particles (Zeman and Zydney, 1996). In this case, formation of the particle-packed (cake) layer is suppressed by shear-induced back transport of the particles. Based on fluid dynamics, lateral migration theory and the score model, the lift velocity is defined as being equal to the steady-state flux (Shimizu

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et al., 1993; Furukawa *et al.*, 2008).

We have studied lactic acid fermentation by *Streptococcus bovis* using fresh cassava roots (FCRs) as the substrate (Ghofar *et al.*, 2005; Yuwono and Kokugan, 2007). In the present study, we evaluate the cross-flow microfiltration properties of the fermentation broth, propose an analytical method for characterizing the cake in the cross-flow filtration and make comparisons between the cake characteristics of dead-end and cross-flow filtrations. We also investigate the effects of the operating conditions (transmembrane pressure, cross-flow velocity and cell concentration) on permeate flux, cake resistance and specific cake resistance.

1. Basic Considerations

The permeate flux (Jv) during filtration in both dead-end and cross-flow filtrations is generally expressed as follows by Eq. (1).

$$Jv = \frac{\Delta P_m}{R_m \mu} = \frac{\Delta P_c}{R_c \mu} = \frac{\Delta P}{\mu(R_m + R_c)} \tag{1}$$

Here, ΔP_m is the pressure difference between the membrane and permeation sides, ΔP_c is the pressure difference between the cake surface and the membrane surface, R_m is the membrane resistance, R_c is the cake resistance and μ is the viscosity of the permeate. The total pressure during filtration (ΔP) is defined by Eq. (2).

$$\Delta P = \Delta P_m + \Delta P_c \tag{2}$$

The cake resistance, R_c, is proportional to the cake weight, W_c, on the membrane surface area, A. This relationship is expressed as follows by Eq. (3).

$$R_c = \alpha \frac{W_c}{A} \tag{3}$$

Here, α is the specific cake resistance.

The relationship between specific cake resistance (α) and cake porosity (ε) can also be interpreted by using the Kozeny–Carman relation and gives the well established empirical relationship for conventional filtration of Eq. (4).

$$\alpha = \frac{K(1-\varepsilon)S_v^2}{\rho_s \varepsilon^3} \tag{4}$$

Here, K is the Kozeny constant and S_v is the particle surface area per unit volume and ρ_s is the particle density.

The relationship between the specific cake resistance (α) and the transmembrane pressure (ΔP) can be expressed experimentally by Eq. (5).

$$\alpha = \alpha_o \Delta P^n \tag{5}$$

Here, n is the cake compressibility and α_o is a constant fixed by the particle size and shape.

1.1 Determination of specific cake resistance in dead-end filtration

In the dead-end filtration, the permeate flux is defined by Eq. (6).

$$Jv = \frac{1}{A}\frac{dV}{dt} \tag{6}$$

Here, V is the permeate volume, t is the filtration time and A is the membrane surface area. With the assumption that the liquid contained in cake can be neglected compared to the amount of filtrate, the cake mass (W_c) can be calculated in relation to the permeate volume (V) and concentration of wet cell (C) using Eq. (7).

$$W_c = CV \tag{7}$$

Combining Eq. (3) and Eq. (7) results in the following relationship shown in Eq. (8).

$$R_c = \alpha \frac{CV}{A} \tag{8}$$

The basic method for determining the specific cake resistance is to measure the permeate volume (V), as a function of time, t, during a batch filtration at constant pressure. Combining Eqs. (1), (6) and (8) gives the following relationship of Eq. (9).

$$\frac{1}{A}\frac{dV}{dt} = \frac{\Delta P}{\mu(R_m + \alpha CV/A)} \tag{9}$$

Equation (9) can be integrated to give the well-known expression of Eq. (10).

$$\frac{t}{V} = \frac{\alpha \mu C}{2A^2 \Delta P} V + \frac{\mu R_m}{A \Delta P} \tag{10}$$

Therefore, α can be determined from the slope of a plot of t/V versus V.

1.2 Determination of specific cake resistance in cross-flow filtration

In the cross-flow filtration, the permeate flux decreases within a relatively short time until reaching a pseudo-steady state that is caused by the cake accumulation on the membrane surface. The cake filtration model (Zeman and Zydney, 1996) assumes that the accumulation of particles on the membrane (W_c*) is proportional to both the particle concentration, C, and the difference between the permeate flux, Jv, and the hydraulic lift velocity of the particles. In this case, the formation of the particle-packed (cake) layer is suppressed by shear-induced back transport of the particles. Based on fluid dynamics, lateral migration theory and the score model, the lift velocity is defined as being equal to the pseudo-steady state flux, Jv* (Shimizu *et al.*, 1993; Furukawa *et al.*, 2008) by Eq. (11) or (12).

$$\frac{1}{A}\frac{dW_c^*}{dt} = (Jv - Jv^*)C \tag{11}$$

$$\frac{W_c^*}{A} = \int_0^{t^*} (Jv - Jv^*)dt \; C \tag{12}$$

The accumulation of particle or cake weight on the

Table 1 Physical properties of the fermentation broth

Properties	
Density of broth (ρ_b) [kg/m^3]	1170 (39°C, C = 7.5 g/L)
Density of permeate (ρ_p) [kg/m^3]	1130 (39°C)
Viscosity of broth (μ_b) [Pa · s]	1.122×10^{-3} (39°C, C = 7.5 g/L)
Viscosity of permeate (μ) [Pa · s]	1.029×10^{-3} (39°C)
	1.325×10^{-3} (25°C)
Concentration of cell (C) [g/L]	1.2; 4.5; 7.5; 10.4
Concentration of lactic acid (C_{LA}) [g/L]	18.8
Concentration of residual sugar (C_{RS}) [g/L]	5.3

membrane surface (W_c*) until the pseudo-steady state in Eq. (13) was calculated using numerical integration-trapezium method of Jv-t plot from $t = 0$ to $t = t$* with Excel® Visual Basic, in which t* is the time to reach the pseudo-steady state flux. Cake resistance at pseudo-steady state (R_c*) was calculated as follows using Eq. (13).

$$Jv^* = \frac{\Delta P}{\mu(R_m + R_c^*)} \tag{13}$$

In present study, the specific cake resistance for cross-flow filtration (α*) is defined by Eq. (14).

$$\alpha^* = \frac{R_c^*}{W_c^*/A} \tag{14}$$

The specific cake resistance of the cross-flow filtration (α*) was then compared to that of the dead-end filtration (α) using Eq. (15).

$$\eta_\alpha = \frac{\alpha^*}{\alpha} \tag{15}$$

Here, η_α is a ratio of the specific cake resistance for the cross-flow to that of the dead-end filtrations.

2. Experimental

2.1 Fermentation broth

Production of lactic acid from fermentation of fresh cassava roots (FCRs) as the raw material and *Streptococcus bovis* as the train was conducted according to the method described in previous literature (Yuwono and Kokugan, 2007). The fermentation broth thus obtained contained 18.8 g/L lactic acid, 5.3 g/L residual sugar.

To measure the dry cell concentration, 20 mL of sample was centrifuged at 2000 rpm for 20 min, and then rinsed twice with deionized water. The sample was then placed in a drying oven at 105°C for 24 h. The wet cell concentration was calculated with respect to the water content of the bacteria cells (70%) (Shimizu *et al.*, 1993). The bacterial cell concentration obtained was about 14 g/L. The cell concentration in the fermentation broth was then varied according to the following steps. First, the fermentation broth was decanted. Next, the volume of sediment containing bacterial cells and the volume of supernatant were varied in order to obtain the desired cell concentration from 1.2 to 10.4 g/L. The physical properties of the fermentation broth are summarized in **Table 1**.

2.2 Dead-end filtration

The dead-end filtration experiment was carried out in a 300 mL batch tank (Model UHP-76, Toyo Roshi Kaisha, Ltd.). Polytetrafluoride ethylene (PTFE) microfiltration with a pore size of 0.1 μm and diameter of 76 mm was used. Pretreatment of the membrane was conducted by filtering an isopropyl alcohol solution. The temperature was controlled to about 25°C by an air conditioner. The feed volume used was 150 mL, and the applied pressure was controlled with pressurized N_2 gas from a gas cylinder and monitored by a pressure transmitter. The permeate was collected on a digital balance, and data were recorded using data acquisition by a personal computer.

2.3 Cross-flow filtration

A cross-flow filtration flow diagram is shown in **Figure 1**. The cross-flow filtration experiments were conducted in a ceramic monolith-type membrane (Cefilt, NGK Filtech, Ltd.) 50 cm long, with 37 holes of 3 mm diameter and a surface area of 0.174 m^2. Microfiltration membranes with 0.1-μm pore sizes were used. A recirculation pump (Type MDG-H15KA200, Iwaki Co., Ltd.) with an inverter was used to adjust the flow rate manually to 5, 7 and 9 L/min, values equivalent to cross-flow velocities of 0.32, 0.45 and 0.58 m/s, respectively. The pressure was adjusted manually within the range of 20–200 kPa by a valve in the retentate stream, and was then monitored by a pressure gauge. The temperature was controlled to 39°C by a water bath, similarly to the operating temperature of membrane bioreactor. The permeate flux data were collected and recorded by a digital balance connected to a personal computer for data acquisition. The permeate was then recycled back into the feed tank to ensure a constant concentration of cells and other compounds. The observed rejection (R_{obs}) of lactic acid was 0 and R_{obs} of residual sugar was nearly 0. The viscosity of the permeate was determined by an Oswald

Table 2 Membrane specification

Specification	Dead-end	Cross-flow
Type	Microfiltration	Microfiltration
Pore size	0.1 μm	0.1 μm
Type	Flat	Monolith
Material	PTFE	Ceramic Al_2O_3
Diameter (d)	76 mm	Hole diameter 3 mm Module diameter 30 mm
Length (l)	—	500 mm
Hole number	—	37
Surface area (A)	4.53×10^{-3} m^2	0.174 m^2
Membrane resistance (R_m)	0.06×10^{12} m^{-1} (water at 25°C)	3.3×10^{12} m^{-1} (water at 25°C and 39°C)

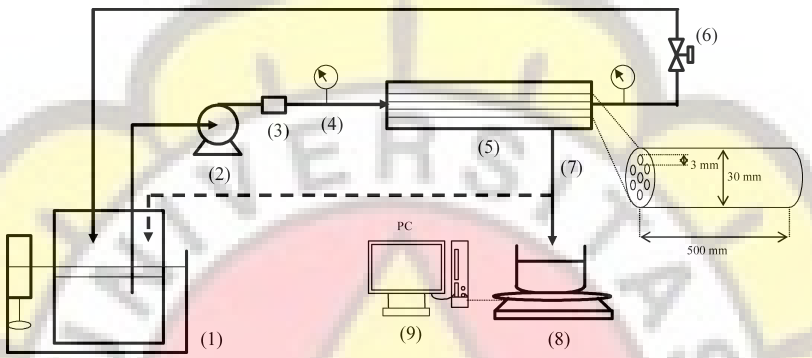

Fig. 1 Experimental setup for a cross-flow filtration: (1) feed tank with water bath; (2) recirculation pump; (3) flow meter; (4) pressure gauge; (5) membrane module; (6) pressure valve; (7) permeate flow; (8) digital balance; (9) computer for data acquisition

viscometer. The membrane specifications for dead-end and cross-flow filtrations are summarized in **Table 2**.

After each experiment, backwash cleaning of the membrane was conducted first with water. Thereafter, it was cleaned with water, a NaClO solution (1 wt%), hot water 50°C, and a NaOH solution (1 wt%) for 1 hour each. Finally, it was rinsed with water for neutralization. The membrane resistance (R_m) was nearly constant for each experimental run.

3. Results and Discussion

3.1 Characterization of filtration properties in the dead-end filtration

The specific cake resistance (α) was calculated using Eq. (9) from the slope of t/V-V plot. The specific cake resistance (α) was then plotted logarithmically against transmembrane pressure, as shown in **Figure 2**. It shows that the specific cake resistance (α) increased with increasing transmembrane pressure (ΔP). Using Eq. (5), the cake compressibility (n) was given by the slope, which was found to be equal to 1.0. The cake compressibility in this study was then compared to the compressibilities observed in other works, as shown in **Table 3**. It can be seen that the cake compressibility of *S. bovis* is

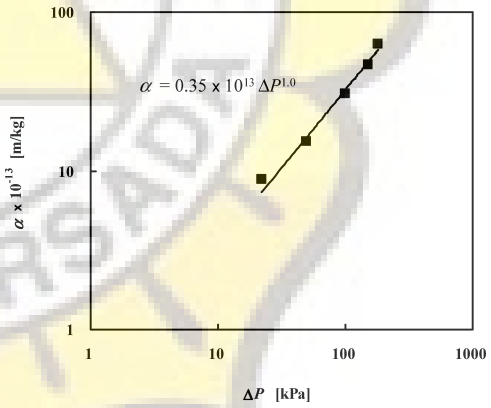

Fig. 2 The effect of transmembrane pressure on specific cake resistance in dead-end filtration at $C = 7.5$ g/L

higher than those of other microorganisms, almost all of which are less than 1. This value indicates that *S. bovis* in cassava broth is more compressible than the others. There is evidence that filter cake compressibility is morphology dependent. As a general rule, rod-like cells tend to have greater cake compressibility than ellipsoidal. In the other studies, there is a difference between the compressibility of the same microorganism in different broths.

Table 3 Comparison of cake compressibilities in dead-end filtration ($\alpha = \alpha_o \Delta P^n$)

Microorganism	Broth	Product	n [—]	References
Streptococcus bovis	Fresh cassava roots	Lactic acid	1.0	Present work
Lactobacillus delbrueckii	Maltose	Lactic acid	0.63	Carrere *et al.* (2001)
Bacillus subtilis	Glucose	Biosurfactant	0.8	Juang *et al.* (2008)
Bacillus subtilis	Standard medium	Biosurfactant	0.8	
Escherichia coli	Standard medium	Cell	0.5	Tanaka *et al.* (1996)
Lactobacillus delbrueckii	Standard medium	Lactic acid	1.0	
Saccharomyces cerevisiae	—	Ethanol	0.39	Keskinler *et al.* (2004)
Saccharomyces cerevisiae	—	Ethanol	0.85	Kumar and Roy (2008)

n = cake compressibility

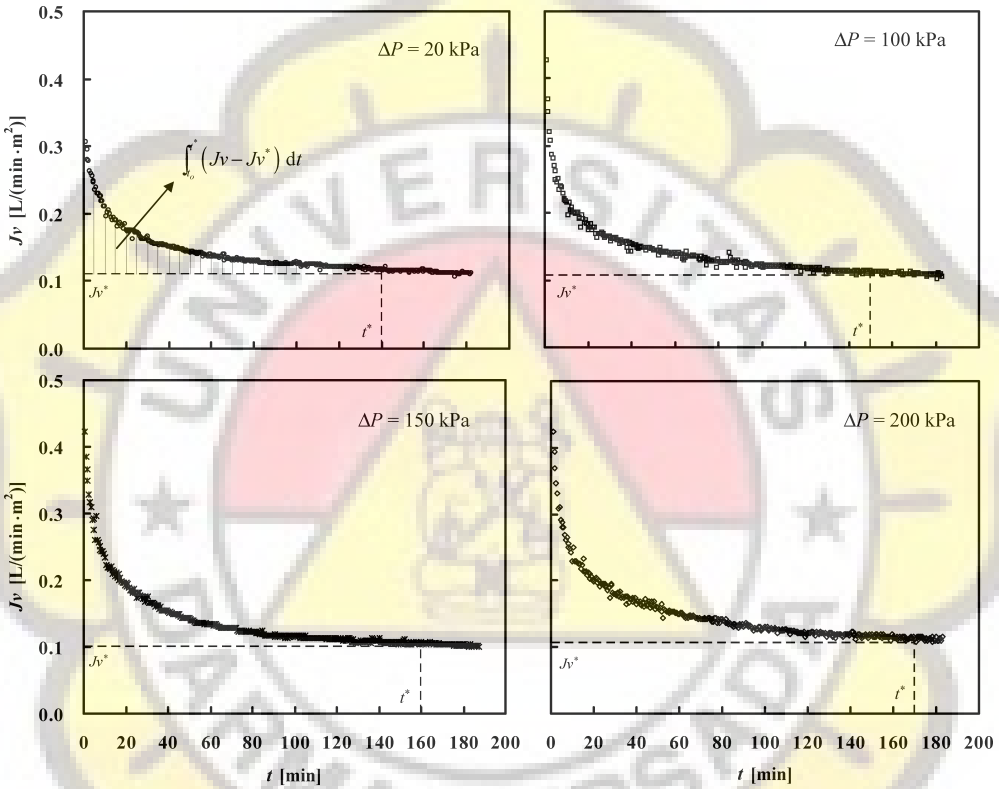

Fig. 3 The effect of transmembrane pressure on permeate flux in cross-flow filtration at u = 0.45 m/s and C = 7.5 g/L

3.2 Filtration properties of cross-flow filtration

Figure 3 shows the permeate flux (Jv) and filtration time (t) at a cross-flow velocity (u) of 0.45 m/s and cell concentration (C) of 7.5 g/L for various transmembrane pressures (ΔP). It can be observed that the permeate flux decreases rapidly at the beginning of the filtration, and continues to decrease until a pseudo-steady state flux (Jv*) is reached for all transmembrane pressures. This decrease in permeate flux with time is due to the cake layer build-up on the membrane surface. Figure 3 also shows that the time required to reach the pseudo-steady state condition (t*) increases with increasing transmembrane pressure. Since the cross-flow filtration of suspensions generates a shear stress on the membrane surface, the cake formation is suppressed and the operation can continue for a long time. A similar flux decline with time for the separation of cells from the fermentation broth in cross-flow filtrations has also been reported by various researchers (Tanaka *et al.*, 1996; Carrere *et al.*, 2001; Juang *et al.*, 2008).

The pseudo-steady state flux (Jv*) relative to transmembrane pressure was then plotted, as shown in **Figure 4**. It can be seen that the permeate flux was not affected by the transmembrane pressure under the present experimental conditions. The independence of the permeate flux and transmembrane pressure was a result of cake compression, as will be explained in the following section.

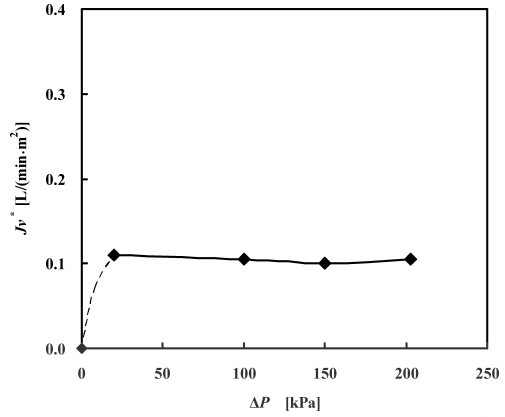

Fig. 4 The effect of transmembrane pressure on pseudo-steady state permeate flux in cross-flow filtration at $u = 0.45$ m/s and $C = 7.5$ g/L

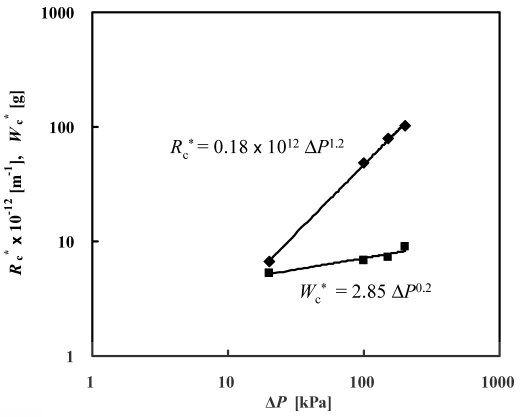

Fig. 5 The effect of transmembrane pressure on cake resistance and cake weight in cross-flow filtration at $u = 0.45$ m/s and $C = 7.5$ g/L

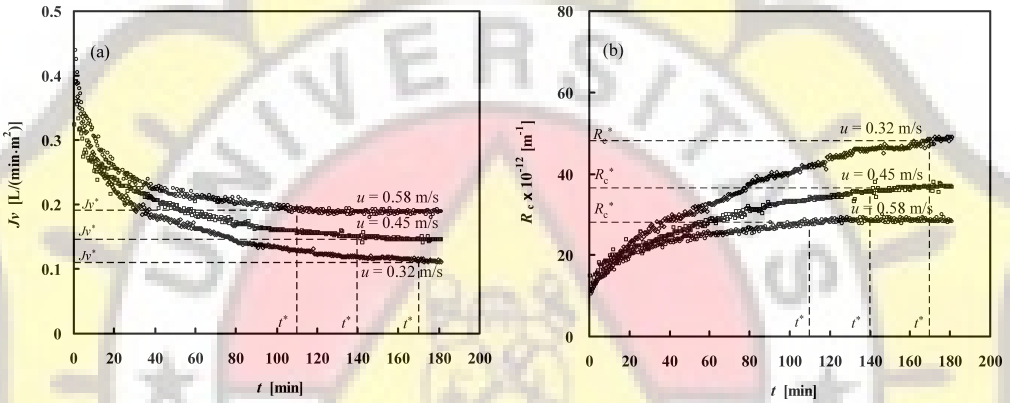

Fig. 6 The effect of cross-flow velocity on permeate flux (a) and cake resistance (b) in cross-flow filtration at $\Delta P = 100$ kPa and $C = 4.5$ g/L

The dependence on the transmembrane pressure was apparently similar to that observed in a study of the cross-flow filtration of lactic acid-producing bacteria by Persson *et al.* (2001). They observed an independence of the permeate flux and transmembrane pressure at pressures above 100 kPa and a high cross-flow velocity (5.3–10.8 m/s). Similar results were also reported by Shimizu *et al.* (1993), who studied the separation of baker's yeast. The permeate flux did not change with increasing transmembrane pressure starting at about 40 kPa. However, Furukawa *et al.* (2008) reported that the permeate flux decreased with increasing transmembrane pressure in the separation of soy sauce lees. Hwang *et al.* (2001) also observed a similar tendency for the separation of *Pseudomonas*.

The cake weight (W_c*) calculated by numerical integration-trapezium method and cake resistance (R_c*) at pseudo-steady state filtration for various transmembrane pressures is shown in **Figure 5**. It can be seen that cake weight and cake resistance increased with increasing transmembrane pressure with the power factors of 0.2 and 1.2, respectively. This is presumably due to the amount of liquid surrounding the particle decreasing with an increase in transmembrane pressure resulting in the more dense cake layer. The present results are in agreement with those of prior studies (Carrere *et al.*, 2001; Juang *et al.*, 2008).

The variation in filtration flux over time in the cross-flow microfiltration of *S. bovis* fermentation broth at various cross-flow velocities (u) is shown in **Figure 6(a)**. The filtration pressure of the suspension (ΔP) was kept at 100 kPa and the initial cell concentration (C) was 4.5 g/L during the filtration process. The plot shows that an increase in the cross-flow velocity leads to a higher filtration flux. This trend is observed because the gel polarization thickness decreases and the cell particles on the membrane surface are also removed by the shear stress under a higher cross-flow velocity. The result is a lower cake resistance (**Figure 6(b)**). Many researchers (Shimizu *et al.*, 1993; Tanaka *et al.*, 1994; Hwang and Lin, 2005) also reported the effects of the cross-flow velocity on the permeate flux in microorganism separations

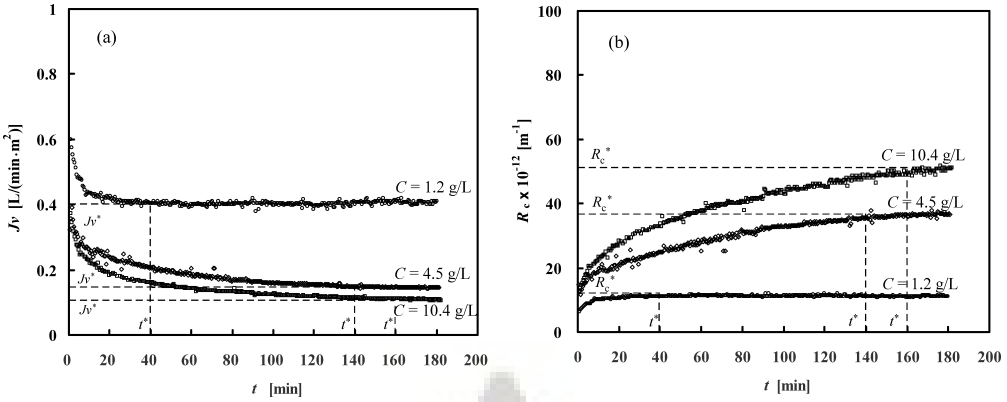

Fig. 7 The effect of cell concentration on permeate flux (a) and cake resistance (b) in cross-flow filtration at $\Delta P = 100$ kPa and $u = 0.45$ m/s

and found similar results. Furthermore, Figure 6 shows that less time is required to reach a pseudo-steady state flux (t^*) at a high cross-flow velocity than at a low cross-flow velocity. This result is in agreement with the findings of Keskinler *et al.* (2004) and Tanaka *et al.* (1993).

Figure 7 shows the effect of cell concentration on the permeate flux (a) and cake resistance (b) at a transmembrane pressure (ΔP) of 100 kPa and a cross-flow velocity (u) of 0.45 m/s. The permeate flux decreased with increasing cell concentrations from 1.2 to 10.4 g/L, and a pseudo-steady state flux (Jv^*) was obtained faster at lower cell concentrations than at higher cell concentration (Figure 7(a)). On the other hand, the cake resistance (R_c) increased with increasing cell concentration (Figure 7(b)). This effect could be due to the increase in the cake thickness on the membrane surface as the cell concentration increases and reduces the permeate flux. This result was in agreement with a study done by Keskinler *et al.* (2004) using cross-flow filtration for the separation of *Saccharomyces cerevisiae* with yeast concentrations varying from 0.5 to 5 g/L. In terms of deposit thickness, Hamachi and Peuchot (1999) found that an increase in the feed concentration caused an increase in the deposit thickness on the membrane surface, resulting in a decrease of the permeate flux when they filtered bentonite suspensions by cross-flow filtration.

3.3 Specific cake resistance in cross-flow filtration

The specific cake resistance in cross-flow filtration (α^*) was determined using Eq. (14). The amount of cake accumulating on the membrane surface to reach the pseudo-steady state per membrane surface area (W_c^*/A) was calculated from Jv-t plot (Figures 3, 6(a) and 7(a)) by the method mentioned in the basic consideration section. The effect of the operating conditions (transmembrane pressure, cross-flow velocity and cell concentration) on α^* was evaluated. The ratios of specific cake resistance (η_α) between cross-flow and dead-end filtrations was then calculated using Eq. (15).

3.3.1 The effect of transmembrane pressure on specific cake resistance

Figure 8 shows the specific cake resistance in cross-flow filtration (α^*), specific cake resistance in dead-end filtration (α) and their ratio $\eta_\alpha = \alpha^* / \alpha$ at transmembrane pressures (ΔP) of 20–200 kPa, a cross-flow velocity of 0.45 m/s and a cell concentration of 7.5 g/L. It can be seen that α^* has trends similar to those of α, in that the specific cake resistance increased with increasing transmembrane pressure.

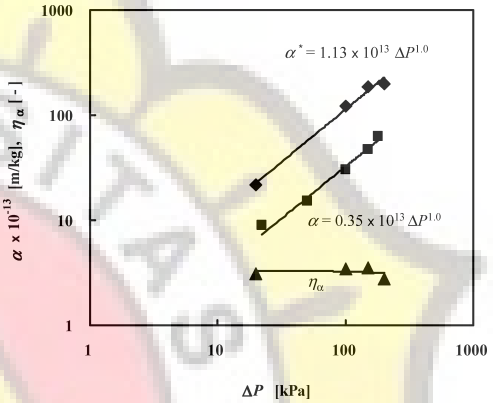

Fig. 8 The effect of transmembrane pressure on specific cake resistance in cross-flow filtration ($u = 0.45$ m/s, $C = 7.5$ g/L) and dead-end filtration ($C = 7.5$ g/L)

In terms of cake porosity, Hwang *et al.* (2001) observed the effects of transmembrane pressure on cake porosity using pseudomonas in two parallel-plate cross-flow microfiltrations. They found that the cake porosity decreased with increasing pressure due to the compression effect. The cake porosity was reduced from 0.6 to 0.5 when the transmembrane pressure increased from 35 to 140 kPa. Their results strengthen the fact that specific cake resistance increases with increasing transmembrane pressures as described by the Kozeny–Carman correlation, Eq. (4).

The slope of the log–log plot of specific cake resistance against transmembrane pressure, which is known as cake compressibility (n), was then determined by Eq. (5). It was found that the cake compressibility of the

cross-flow filtration ($n = 1.0$) was similar to that of the dead-end filtration ($n = 1.0$). From this result, it can be understood that a compressible cake is formed in the cross-flow filtration from the increasing transmembrane pressure and has a similar behavior with the dead-end filtration.

Furukawa *et al.* (2008) conducted cross-flow microfiltration of soy-sauce lee and reported that the specific cake resistance of the soy sauce lees cake formed on the membrane surface also increased with increasing transmembrane pressure, the cake compressibility being 1.81. Tanaka *et al.* (1994) also reported the specific cake resistance of *B. subtilis* in cross-flow filtration and found that the cake compressibility was about 0.6.

Carrere *et al.* (2001) modeled the cross-flow filtration of *Lactobacillus delbrueckii* in a lactic acid fermentation broth. They used the cake compressibility calculated from the dead-end filtration ($n = 0.63$) to determine the specific cake resistance in cross-flow filtration with the assumption that both processes have the same cake compressibility. Juang *et al.* (2008) also used the cake compressibility in dead-end filtration to determine the specific cake resistance of *Bacillus subtilis* in a biosurfactant fermentation broth by cross-flow filtration. The present study has proved that the cake compressibilities for both cross-flow and dead-end filtrations are similar.

Figure 8 also shows that the ratio of specific cake resistance in the cross-flow filtration to that in the dead-end filtration (η_α) is about 3.5 for all transmembrane pressures at a given cross-flow velocity. Tanaka *et al.* (1996) found similar results when they conducted filtration of rod-shaped bacteria in a cross-flow. They observed that the specific cake resistance in cross-flow filtration at a cross-flow velocity of 0.5 m/s is 4 times higher than that of the dead-end filtration. In the cross-flow filtration, cells tended to be arranged parallel to the circulation flow above the randomly deposited layer, resulting in a decreased distance between cells or decreased cake porosity. The *S. bovis* used in this study is a sphere-type cell which grows in a chain or pairs to form chain-like bacteria cells. We assumed that the chain-like *S. bovis* behavior is similar to that of the rod-type cell used in the study by Tanaka *et al.* (1996). Keskinler *et al.* (2004) also reported that the specific cake resistance in a cross-flow is higher than that in a dead-end filtration using *Saccharomyces cerevisiae*.

3.3.2 The effect of the cross-flow velocity on the specific cake resistance **Figure 9** shows the effect of the cross-flow velocity (u) on the specific cake resistance (α^*) at a transmembrane pressure of 100 kPa and cell concentration of 4.5 g/L. The specific cake resistance at the cross-flow velocity of 0 m/s as shown in this figure is the specific cake resistance in the dead-end filtration, which is lower than that in the cross-flow filtration. Increasing the cross-flow velocity from 0.32 to 0.58 m/s causes the specific cake resistance (α^*) to increase. This

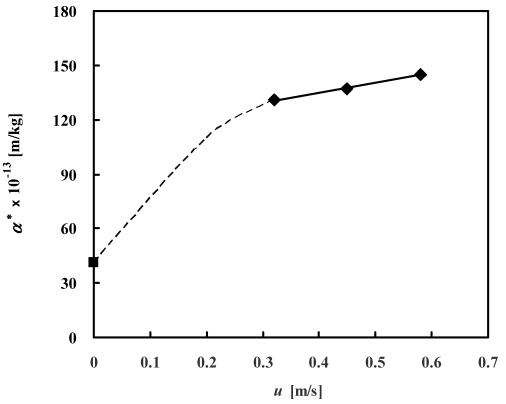

Fig. 9 The effect of cross-flow velocity on specific cake resistance and in crossflow filtration at $\Delta P = 100$ kPa and $C = 4.5$ g/L

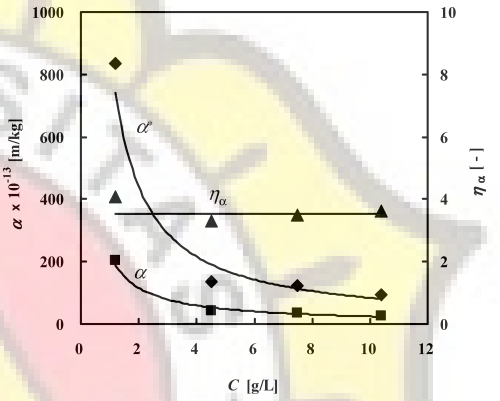

Fig. 10 The effect of cell concentration on specific cake resistance in cross-flow filtration ($u = 0.45$ m/s, $\Delta P = 100$ kPa) and dead-end filtration ($\Delta P = 100$ kPa)

could be due to the increase of the shear stress on the microbial cake as the cross-flow velocity increased resulting in better cell arrangement having less cake porosity and high specific cake resistance (Eq. (4)). This result was in agreement with the study by Tanaka *et al.* (1994).

However, using UF and MF polysulfone flat-type membranes for the separation of soy sauce lees, Furukawa *et al.* (2008) showed the result that specific cake resistance (a) decreased with increasing the cross-flow velocity.

3.3.3 The effect of cell concentration on specific cake resistance and cake resistance **Figure 10** shows the effect of cell concentration on the specific cake resistance at a transmembrane pressure (ΔP) of 100 kPa and a cross-flow velocity of 0.45 m/s. It can be seen that the specific cake resistance in both dead-end (α) and cross-flow (α^*) filtrations decreased with increasing cell concentration at cell concentrations from 1.2 to 4.5 g/L. However, the specific cake resistance was hardly changed by cell concentrations above 4.5 g/L.

The phenomenon of decreasing specific cake resistance with increasing cell concentration can be explained by the fact that the average distance between particles is smaller at higher concentrations, and the tendency for the particles to be drawn into the streamlines directed to the open pores is diminished (Ho and Sirkar, 1992).

A similar trend was also reported by Keskinler *et al.* (2004) using non-living yeast suspensions, where the specific cake resistance decreased with increasing cell concentration at concentrations less than 1 g/L, and then was independent with the change of cell concentration at concentrations higher than 1 g/L. Tanaka *et al.* (1994) observed that the specific cake resistance was nearly constant in cell concentrations from 1.25 to 10 g/L when filtering *Bacillus subtilis* in cross-flow filtration. Figure 10 also shows that h_a was about 3.5 for all cell concentrations.

Conclusions

The cross-flow microfiltration characteristics of bacterial cells (*S. bovis*) from a lactic acid fermentation broth using fresh cassava roots as a raw material has been investigated. The amount of particles accumulated on the membrane surface (W_c*) was evaluated using a cake filtration model. In cross flow filtrations, the specific cake resistance increased with increasing transmembrane pressure (ΔP), and the cake compressibility was about 1.0, which is similar to the cake compressibility in dead-end filtration. The specific cake resistance in the cross-flow filtration (α*) was higher than that in the dead-end filtration (α). The ratio of the specific cake resistance in cross-flow to that of a dead-end filtration (η_α) was about 3.5. This is because, in the cross-flow filtration, cells tended to be arranged parallel to the circular flow above a randomly deposited layer, resulting in a decreased distance between cells or decreased cake porosity. The α* increased with increasing cross-flow velocity. This increase was due to the fact that the increase in shear stress with increasing cross-flow velocity resulted in a decrease in the cake porosity. The specific cake resistance decreased with increasing cell concentration until a concentration at which the specific cake resistance hardly changed. The ratio of the specific cake resistance in the cross-flow to that in the dead-end filtration (η_α) was about 3.5 at varied cell concentrations.

Nomenclature

A	=	membrane surface area	[m^2]
C	=	wet cell concentration	[g/L]
Jv	=	permeate flux	[L/(min · m^2)]
Jv*	=	permeate flux at pseudo-steady state	[L/(min · m^2)]
K	=	Kozeny constant	[—]
n	=	cake compressibility	[—]
R_c	=	cake resistance	[m^{-1}]
R_c*	=	pseudo-steady-state cake resistance in the cross-flow filtration	[m^{-1}]
R_m	=	membrane resistance	[m^{-1}]
R_{obs}	=	observed rejection	[—]
S_v	=	particle surface area per unit volume	[m^2/m^3]
t	=	filtration time	[min]
t*	=	pseudo-steady state filtration time	[min]
u	=	cross-flow velocity	[m/s]
V	=	permeate volume	[mL]
W_c	=	dry cake weight with wet cells	[g]
W_c*	=	dry cake weight with wet cells in cross-flow filtration	[g]
α	=	specific cake resistance	[m/kg]
α*	=	specific cake resistance in a cross-flow filtration	[m/kg]
α_o	=	a constant fixed by the particle size and shape	[—]
ΔP	=	transmembrane pressure	[kPa]
ΔP_c	=	pressure difference between the cake surface and the membrane surface	[kPa]
ΔP_m	=	pressure difference between the membrane and permeation sides	[kPa]
ε	=	cake porosity	[—]
η_α	=	ratio of the specific cake resistance for the cross-flow to that of the dead-end filtration	[—]
μ	=	viscosity of the permeate	[Pa · s]
μ_b	=	viscosity of broth	[Pa · s]
ρ_b	=	density of broth	[kg/m^3]
ρ_p	=	density of permeate	[kg/m^3]
ρ_s	=	particle density	[kg/m^3]

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