Effect of Polysaccharide Concentration on the Membrane Filtration of Microbial Cells

Kuo-Jen Hwang1*, Pei-Chun Tsai1, Eiji Iritani2 and Nobuyuki Katagiri2

1Department of Chemical and Materials Engineering, Tamkang University, Tamsui, Taiwan 251, R.O.C.
2Department of Chemical Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

Abstract

Polysaccharides are frequently produced by microbial metabolism or lysis in fermentation broths or bioreactors. This substance often causes membrane filtration difficulty. The polysaccharide concentration effects on the microfiltration characteristics of microbial cells are discussed in this study. Yeast and dextran are used as typical microbial cell and polysaccharide samples. The results show that polysaccharides play important roles in filtration performance. The filter cake exhibits a more compact structure and much higher filtration resistance when more dextran molecules pack into the yeast cake structure. Some dextran molecules also adsorb onto the walls in membrane pores, reducing the pore size, resulting in membrane fouling. The filtration resistances due to filter cake and membrane internal fouling are analyzed using filtrate volume versus time experimental data. These resistances increase significantly with the filtration pressure and dextran concentration. The cake properties in constant pressure microfiltration of yeast-dextran mixtures with different compositions are also analyzed. An increase in dextran concentration leads to lower cake growth rate, lower cake porosity and much higher average specific cake filtration resistance.

Key Words: Microfiltration, Membrane Filtration, Bio-Separation, Cake Properties

1. Introduction

Microfiltration has been widely used in the primary product purification step in fermentation broths or bioreactors in recent years. In such biological mixture microfiltration, microbial cells are retained by the filter membrane to form a filter cake. Small components such as polysaccharides, proteins, etc., are able to penetrate through the membrane into the filtrate. The filtration resistance may be markedly increased due to the packing of polysaccharides or proteins into cake structures [1]. As a result, ignoring this effect will cause an extremely low filtration rate as well as higher operating costs.

Although many methods have been proposed for analyzing filtration data [2], the cake properties are usually related to the filtration pressure using power-type empirical equations for simplicity [3]. However, the cakes formed by deformable or soft particles, such as biological particles, may exhibit viscoelastic behaviors (creeping effects) during compression [4–6]. These lead the filtration curve of \( \frac{dt}{dv} \) vs. \( v \) (the reciprocal of filtration rate versus filtrate volume) to deviate in a straight line and the cake properties are therefore functions of the filtration time [4,5]. The variations in cake properties, such as cake porosity, specific cake filtration resistance and cake compressibility, during a filtration are related to the operating conditions but also the particle physical properties, e.g., particle softness, relaxation time of particle compression, etc. [5,6]. Most cake compressions occur in the early filtration periods, which lead to forming a compact cake layer with high cake compressibility and high cake filtration resistance. Because most
hydraulic pressures are depleted in the compact cake layer, the newly formed cake layers have loose structures and low filtration resistances. Therefore, the cake compressibility gradually decreases after reaching a maximum [5,6]. This phenomenon is also seen in microbial cell filtration [1,7]. Because most biological materials are highly compressible, a thin but compact and high resistance cake layer is often formed next to the membrane surface during microfiltration [7–11]. In the past, several researchers focused on the operating condition effects on microbial cell filtration performance. For example, the microfiltration behavior of pseudomonas was studied by Hwang et al. [7]. The formation of a compact cake layer was simulated using a dynamic analysis method and verified by experimental data. McCarthy et al. [11] studied the dead-end filtration of yeasts with different morphologies. They found that the cake compressibility increased with increasing the mean aspect ratio and deformability of yeast cells.

The cake structure and composition play important roles in determining the cake filtration resistance. In general, the biological suspensions in fermentation broths or bioreactors contain multiple components. Polysaccharides, proteins or enzymes disperse with microbial cells due to metabolism, lysis or bio-reaction. The filtration performance may be significantly affected due to the coexistence of these small components [1]. Hung and Liu [12] studied the separation of green algae from water using cross-flow microfiltration. The filtration flux decreased unexpectedly with increasing filtration pressure. This phenomenon was attributed to the increase in suspended polysaccharides. Hwang and Yang [1] studied the influence of dextran on the dead-end microfiltration of yeast cells. They indicated that the existence of dextran in the cake structure resulted in more compressible and much higher filtration resistance cakes. However, the cake packing structure and filtration resistance may also be significantly affected by the concentration of small components. Devoting more effort to this subject for further study is worthwhile.

When multiple components with a wide particle size distribution are filtered in a microfiltration process, the filtration resistances may be caused by the filter cake on the membrane surface or by membrane pore blocking. For instance, some researchers claimed that the main filtration resistance was attributed to the cake formed by the suspended particles in membrane bioreactors [13, 14]. Conversely, others indicated that internal fouling in the membrane pores was the main source of filtration resistance [15]. In fact, both resistances may occur individually or simultaneously depending on the operating conditions, suspension characteristics and membrane properties.

Dextran and yeast were used as typical samples in this study to understand how the polysaccharide concentration affected microbial cell microfiltration performance. The filtration rate, cake porosity, specific cake filtration resistance and dextran rejection under various filtration pressures in a dead-end microfiltration process is measured and discussed. The filtration curves were analyzed to obtain the filtration resistances caused by the filter cake and dextran adsorption in the membrane pores. The analyzed results were compared with the available experimental data.

2. Materials and Methods

Baker yeast was purchased from ICN Biomedicals Inc. in Germany. Yeast cells were suspended in deionized water and heated to 80 °C for 20 min to deactify the cells. Dextran with a molecular weight of 2,000 kDa, manufactured by Sigma Co. in USA, was used in these experiments as the polysaccharide sample. Yeast and dextran were suspended in a 10 mM buffer solution prepared using sodium phosphate (Na₂HPO₄) and sodium hypophosphite (NaH₂PO₂). The yeast concentration was fixed at 1 kg/m³, while three dextran concentrations, 0.1, 0.3 and 0.5 kg/m³, were prepared. The bulk density and mean size of the yeast cells were 1140 kg/m³ and 4.6 μm, respectively. The filter membrane was made of mixed cellulose ester manufactured by Millipore Co. in USA. Its mean pore size was 0.025 μm.

Constant pressure dead-end microfiltration experiments were carried out using a bomb filter. The detail was shown in the authors’ previous studies [5,6]. The filtration area in the filter chamber was 8.55 × 10⁻⁴ m². Suspensions with different concentrations were prepared and agitated using a magnetic mixer to prevent particle sedimentation. The pH and temperature of the suspension were 7.0 and 25 °C, respectively. The filtration pressure was supplied using compressed air and adjusted using a regulator. The filtrate was weighed using a load
cell. The filtrate volume data versus time were transferred to a personal computer for further analyses. The dextran concentration in the filtrate was measured using the phenol/sulfuric acid method. The filtrate sample was colored using phenol and dewatered using sulfuric acid. The dextran concentration was then measured using a UNICAM UV/Visible spectrometer with a wavelength of 299 nm. When a filtration experiment was terminated, the cake porosity was analyzed using an infrared-ray moisture meter (AD-4714A, AND Co., Japan) [6].

The filtration resistances are the sum of the resistance due to cake formation, the internal membrane fouling and the virgin membrane. The virgin membrane resistance was measured by penetrating the buffer solution through the membrane before each experiment. The overall filtration resistance was calculated using the filtration rate data. When an experiment was terminated the cake formed on the membrane surface was carefully removed. The filtration resistance due to membrane internal fouling was then measured by flowing a buffer solution through the rinsed membrane. The cake resistance was obtained by subtracting the others from the overall resistance.

3. Results and Discussion

3.1 Filtration Characteristics

According to the resistance-in-series model, the basic filtration equation can be expressed as:

\[
q = \frac{dv}{dt} = \frac{\Delta P}{\mu(R_c + R_f + R_m)}
\]

(1)

where \(q\) is the filtration flux, \(v\) is the received filtrate volume per unit area, \(t\) is the filtration time, \(\Delta P\) is the filtration pressure, \(\mu\) is the fluid viscosity, and \(R_c\), \(R_f\) and \(R_m\) are the filtration resistances caused by the filter cake, membrane internal fouling and virgin membrane, respectively. When pure dextran was filtered most of the dextran molecules penetrated through the membrane pores because they are much smaller than the pore size. In this condition no evident cake can be observed and the measured cake resistance is negligible. The main filtration resistance is therefore caused by membrane internal fouling. The adsorption of dextran molecules onto the membrane pore walls decreases the effective membrane pore size and increases the filtration resistance. This is similar to that observed in previous studies [16,17]. In this condition \(R_c\) is negligible and the reciprocal of Eq. (1) can be written as:

\[
\frac{dt}{dv} = \frac{\mu R_f + \mu R_m}{\Delta P}
\]

(2)

Typical plots for \(dt/dv\) vs. \(v\) during pure dextran filtration under various filtration pressures are shown in Figure 1. The dextran concentration is fixed at 0.5 kg/m². Because the second term on the right-hand-side of Eq. (2) is constant under a given pressure, the increase in \(dt/dv\) value along with \(v\) in Figure 1 is certainly due to the increase in resistance caused by internal membrane fouling, \(R_f\). The membrane fouling resistance increases with increasing received filtrate volume until a maximum value that depends on the filtration pressure. The \(dt/dv\) value (or \(R_f\)) remains constant thereafter. This is attributed to the dextran adsorption equilibrium in the membrane pores. The membrane pore size reduces to a certain value determined by the applied pressure [16–18]. After that equilibrium is attained the dextran molecules that arrive at the membrane surface will penetrate through the membrane pores into filtrate. The filtration resistance is therefore invariant. Comparing the data shown in the figure, the \(dt/dv\) value for a given \(v\) is smaller under higher filtration pressure. This reveals that the filtration rate, which is the reciprocal of \(dt/dv\), is higher under higher filtration pressures. Furthermore,
more dextran adsorption in the membrane pores can be expected under higher pressure since the maximum \( v \) value is larger.

According to the previous analysis, the \( R_f \) value during a constant pressure filtration can be calculated by substituting experimental data of \( v \) vs. \( t \) into Eq. (2). For a given dextran concentration of 0.5 kg/m\(^3\), the relationships between \( R_f \) and \( v \) under three different filtration pressures are shown in Figure 2. The \( R_f \) value increases linearly with \( v \) until a maximum point is attained under a given filtration pressure. It then remains constant thereafter. This is because the filtration resistance caused by membrane fouling is proportional to the filtrate volume flow through the membrane pores, and the dextran adsorption (the foulant) reaches equilibrium at the maximum point. Because additional membrane fouling no longer occurs, the membrane pore size is reduced no more and the filtration resistance remains constant after dextran equilibrium adsorption. The filtration rate therefore remains constant after reaching the equilibrium fouling state [16,18]. It is interesting that the relationship between \( R_f \) and \( v \) before the equilibrium adsorptions are the same even under different filtration pressures. The relationship for \( C_D = 0.5 \) kg/m\(^3\), for example, can be regressed to a unique function as follows:

\[
R_f = 2.12 \times 10^{14} v \tag{3}
\]

The filtrate volume at dextran adsorption equilibrium increases with increasing filtration pressure. This reveals that the membrane fouling becomes more severe under higher applied pressures. This trend is similar to a general adsorption isotherm or those occurring in previous studies [16–18].

It can be inferred from previous analysis that the filtration resistance caused by membrane internal fouling increases with time (or filtrate volume) and finally reaches a maximum (equilibrium) value during constant pressure yeast-dextran mixture filtration. Figure 3 shows comparisons of the maximum \( R_f \) values between the results calculated using the method described in above paragraph and the experimental data under various filtration pressures for yeast-dextran suspensions with different dextran concentrations. The calculated results agree fairly well with the experimental data. This fact demonstrates that the relationships between \( R_f \) and \( v \) for dual and sole dextran suspensions are nearly the same under conditions that most dextran molecules have the opportunity to penetrate through the membrane pores. Furthermore, the \( R_f \) values have an order-of-magnitude of \( 10^{13} \) m\(^{-1}\) and are power functions of \( \Delta P \) given from the regressed curves for the experimental data. These data reveal that the membrane internal fouling plays an important role in determining the overall filtration resistance and the \( R_f \) value will increase drastically with increasing filtration pressure. Comparing the data shown in Figure 3, the \( R_f \) values for different dextran concentrations have similar pressure dependency and increase

![Figure 2. Relationship between \( R_f \) and \( v \) for different filtration pressures.](image-url)
with increasing dextran concentration. This can be expected because more dextran adsorption occurs in the membrane pores under higher concentrations.

Figure 4 shows the filtration curves for $\frac{dt}{dv}$ vs. $v$ for different suspensions under a constant pressure of 300 kPa. When yeast cells coexist with dextran in a suspension, the $\frac{dt}{dv}$ value for a given $v$ becomes much higher than that for single component filtration. This is attributed to the cake formation in which the dextran molecules pack in the pores obstructed by yeast cells. Consequently, the filtration resistance becomes much higher. Since the filtration resistance caused by membrane internal fouling can be estimated using the method described previously, the cake resistance can be given using the difference between the $\frac{dt}{dv}$ data of yeast-dextran and sole dextran suspensions, as shown in Figure 4. In yeast-dextran dual suspension filtration the membrane internal fouling and cake growth occur simultaneously before the filtrate volume reaches a critical value $v_c$ at which the dextran adsorption attains equilibrium. After that, the increase in $\frac{dt}{dv}$ value (or the increase in filtration resistance) is solely due to the cake formation and cake compression. The filtration resistance is much lower and the filtration rate is much higher in the filtration of sole yeast suspension compared to the others. This implies that the polysaccharides or extracellular polymer substances produced by microbial metabolism will play major roles in determining the filtration performance.

The filtration curves, which deduct the contributions of membrane internal fouling from experimental $\frac{dt}{dv}$ data, for the suspensions containing different dextran concentrations during constant pressure filtration are shown in Figure 5. The curves show the cake formation and compression effects on the filtration rate since the virgin membrane resistance affects only the intercept at the beginning. The curve trend is similar to those in previous studies on the filtration of soft or deformable particles [5,6]. Each curve can be divided into three distinct regions. A gradual increase in $\frac{dt}{dv}$ is given in the early filtration periods due to yeast cell deposition. The filtration curve depicts a Ruth-type relation, i.e., linear relationship between $\frac{dt}{dv}$ and $v$ [2,3]. In the second region the tangent slope of each curve increases drastically because of significant cell and cake compression. This effect is mitigated after an inflection point. The curve trend in the third region changes back to that in the first region. This is because most solid compressive pressures are depleted by the compact cake constructed in the second region. Therefore, the newly-formed cake has a looser packing structure and the increase in $\frac{dt}{dv}$ values or the cake growth becomes much slower. The comparison of those curves shown in Figure 5 clearly indicates that the increase in dextran concentration leads to a higher $\frac{dt}{dv}$ value, lower filtration rate and higher cake resistance.

The dextran rejection coefficient, $R_{rej}$, is defined as:

$$R_{rej} = 1 - \frac{C_e}{C_d}$$  (4)

Figure 4. Filtration curves of $\frac{dt}{dv}$ vs. $v$ for suspensions with different components under a constant pressure of 300 kPa.

Figure 5. The filtration curves of $(\frac{dt}{dv} - \mu R_f/\Delta P)$ vs. $v$ for suspensions containing different dextran concentrations during constant pressure filtration.
where \( C_p \) and \( C_d \) are the dextran concentrations in the filtrate and original suspension, respectively. Figure 6 shows how the dextran concentration and filtration pressure affect the dextran rejection after the dextran equilibrium adsorption in the membrane pores, e.g., at 20,000 s. The dextran rejection increases with increasing dextran concentration under a given filtration pressure. When the dextran concentration increases from 0.1 to 0.5 kg/m³, the dextran rejection increases 10–20%. However, the dextran rejection values range from 0.1 to 0.3 in the conditions in this study, which means that most dextran molecules (70–90%) will penetrate through the cake and membrane into the filtrate. Only 10–30% of suspended dextran molecules are constructed into the cake structure. In other words, the dextran contribution to the whole cake mass is less than 15%. The low dextran rejection makes dextran adsorption in the membrane pores able to attain equilibrium even under yeast cake formation conditions. Since more dextran adsorption occurs under higher dextran concentration [18], greater membrane pore size reduction rejects more dextran penetration. The data also shows that an increase in filtration pressure leads to lower dextran rejection for a given dextran concentration. This is attributed to the higher filtration rate. The dextran molecules penetrate through the cake and membrane more easily under quicker filtrate flow. However, this pressure effect becomes smaller under higher dextran concentrations.

### 3.2 Cake Properties

The cake porosity was measured using an infrared-ray moisture meter after filtration experiments. The cake porosity values of yeast cakes with different dextran concentrations under various filtration pressures are summarized in Table 1. It can be expected that the cake porosity decreases with increasing filtration pressure due to greater cake compression. When the dextran concentration increases, more dextran molecules will pack in the yeast cake pores to construct a more compact cake. As a result the cake porosity decreases.

The reciprocal of Eq. (1) can be written as follows:

\[
\frac{dt}{dv} = \frac{\mu R_c}{\Delta P} + \frac{\mu R_f}{\Delta P} + \frac{\mu R_m}{\Delta P}
\]

Once the virgin membrane resistance is measured and \( R_f \) is obtained using the method described previously, e.g., Eq. (3). The cake resistance \( R_c \) can be calculated from the \( dt/dv \) data using the above equation. The cake resistance comparisons under various filtration pressures and dextran concentrations at \( t = 20,000 \) s are shown in Figure 7. The cake resistance increases exponentially with the filtration pressure for a fixed dextran concentration. The cake resistance increases \( ca \) 4 times when the filtration pressure increases from 50 to 300 kPa. This is mainly attributed to more serious cake compression under higher pressures. This also implies that increasing the filtration pressure may not efficiently

![Figure 6. Effects of dextran concentration and filtration pressure on the dextran rejection in microfiltration of yeast--dextran suspensions.](image)

<table>
<thead>
<tr>
<th>( \Delta P ) (kPa)</th>
<th>Pure yeast</th>
<th>( C_D = 0.1 ) kg/m³</th>
<th>( C_D = 0.3 ) kg/m³</th>
<th>( C_D = 0.5 ) kg/m³</th>
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<tbody>
<tr>
<td>50</td>
<td>0.63</td>
<td>0.51</td>
<td>0.50</td>
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<tr>
<td>100</td>
<td>0.60</td>
<td>0.43</td>
<td>0.45</td>
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<td>200</td>
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<td>300</td>
<td>0.56</td>
<td>0.48</td>
<td>0.47</td>
<td>0.45</td>
</tr>
</tbody>
</table>
increase the filtration rate because more hydraulic pressure will be depleted by the drastic increase in cake resistance. An increase in dextran concentration leads to higher cake resistance. This is because packing more dextran molecules into the cake structure causes lower cake porosity and higher filtration resistance. This effect is more significant under higher filtration pressure.

Because all yeast cells will be retained by the filter membrane used in these experiments, the cake mass formed by solely yeast can be calculated using a material balance as shown below.

\[ w_c = C_Y \nu \]  

(6)

where \( C_Y \) is the yeast concentration in the original suspension. However, the dextran molecules also have the opportunity to pack into the cake structure. Their masses should be considered in the cake mass when yeast-dextran mixtures are filtered. Therefore, the cake mass formed by a yeast-dextran mixture can be calculated using

\[ w_c = (C_Y + C_D') \nu = C_Y \nu \]  

(7)

where \( C_D' \) is the dextran concentration contributed to cake formation estimated using the dextran rejection as follows:

\[ C_D' = C_D - C_P = C_D R_{nj} \]  

(8)

The dextran concentration and filtration pressure effects on the cake mass formed in the early 20,000 s are shown in Figure 8. The yeast concentration was set at 1 kg/m³ in all cases. The curves are the results calculated using Eq. (7), while the symbols are experimental data measured using an infrared-ray moisture meter. As in most filtration cases the cake mass increases with increasing filtration pressure. This is attributed to higher filtration rate under higher filtration pressure. The dextran concentration effect is also important in the cake mass. This is because the presence of dextran molecules in the cake structure markedly increases the cake resistance and decreases the filtration rate. The cake growth is therefore much slower under higher dextran concentrations. The cake mass is only 20–30% compared to that of pure yeast cake at the given filtration time when dextran exists in the suspension and decreases with increasing dextran concentration. Comparing the calculated results with the experimental data, underestimations occur only under low filtration pressures, e.g., 50 kPa. This is possibly due to the measurement difficulty for such a small amount of cake. However, Eq. (7) can be used for estimating the cake mass without cake drying.

According to Eq. (7), the cake resistance can be expressed as

\[ R_c = w_c \cdot \alpha_{ps} = C_Y \alpha_{ps} \]  

(9)

where \( \alpha_{ps} \) is the average specific cake filtration resistance. Substituting Eq (9) into Eq. (5) yields

\[ \frac{1}{R_c} = \frac{1}{w_c} \cdot \alpha_{ps} = \frac{1}{C_Y} \alpha_{ps} \]  

(10)
\[ \frac{dt}{dv} = \mu C_{\alpha_{av}} + \frac{\mu R_f}{\Delta P} + \frac{\mu R_{sf}}{\Delta P} \] (10)

Thus, the \( \alpha_{av} \) values during a filtration can be obtained from the tangent slope of the filtration curve of \( \frac{dt}{dv} \) vs. \( v \), e.g., Figure 5. Figure 9 shows the variations in \( \alpha_{av} \) during filtration under \( \Delta P = 50 \) kPa and various dextran concentrations. The \( \alpha_{av} \) value for a given dextran concentration increases quickly in the early filtration period due to serious cake compression. After reaching the maximum value, most hydraulic pressures are depleted by the compact cake structure, the \( \alpha_{av} \) value then decreases and gradually approaches a pseudo-steady value. This trend can be explained by the compression behavior of cakes formed by soft or deformable particles [5,6]. Based on these results, one knows that most cake compressions formed by yeast-dextran mixtures occur before 4,000 s and the cake properties approach pseudo-steady after 20,000 s. The dextran concentration plays an important role in determining the \( \alpha_{av} \) value, especially for the maximum value occurring at the most serious cake compression state. As one’s expectation, an increase in dextran concentration leads to higher \( \alpha_{av} \) value.

According to Tiller’s empirical equations, the relationship between \( \alpha_{av} \) and \( \Delta P \) can be expressed as the following power-type empirical equation [3]:

\[ \alpha_{av} = A\Delta P^n \] (11)

where \( A \) and \( n \) are empirical constants. The \( n \) value is so-called the “cake compressibility” which is an index that indicates the sensitivity of \( \alpha_{av} \) to applied pressure. The \( \alpha_{av} \) values at 20,000 s under various dextran concentrations and filtration pressures are plotted in logarithmic scales in Figure 10. The \( \alpha_{av} \) value increases with increasing \( \Delta P \) value due to more serious cake compression. The \( \alpha_{av} \) value increases 3–5 times when \( \Delta P \) increases from 50 to 300 kPa. The data under various filtration pressures for each suspension can be regressed to a straight line. This reveals that Tiller’s empirical equation, Eq. (11), is appropriate to relate \( \alpha_{av} \) and \( \Delta P \) for the cake formed by yeast-dextran mixtures. The cake compressibility values are not obviously affected by the dextran concentration and are as high as 0.88 even after the major cake compression extent occurs. The \( \alpha_{av} \) value markedly increases due to the existence of dextran molecules in the filter cake. The \( \alpha_{av} \) values for \( C_D = 0.1 \) and 0.5 kg/m\(^3\) become 10-fold and 30-fold, respectively, higher than that of pure yeast cake.

4. Conclusion

The dextran concentration effects on the microfiltration characteristics of yeast cells were studied. Some dextran molecules adsorbed onto the membrane pore walls to reduce the membrane pore size, resulting in membrane fouling until the equilibrium state was reached. The filtration resistances due to filter cake and
membrane internal fouling were analyzed using the $dt/dv$ vs. $v$ filtration curve. These resistances increased markedly with the filtration pressure and dextran concentration. They occurred because the filter cake was more compact as more dextran molecules packed into the cake structure and more dextran molecules adsorbed into the membrane pores. The filtration curves also showed that most of the cake compression occurred in the early filtration period. The cake formed in those periods depleted most hydraulic pressures and exhibited a compact structure and high specific filtration resistance. Most dextran molecules had the opportunity to penetrate through the membrane pores into the filtrate except those packed in the cake pores and adsorbed onto the membrane pore walls. The dextran rejection ranged from 0.1 to 0.3 in the conditions in this study, which means only 10–30% of the suspended dextran molecules were constructed into the cake structure. The cake properties analyses indicated that an increase in dextran concentration led to a lower cake growth rate, lower cake porosity and higher average specific cake filtration resistance.

Acknowledgements

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>empirical constant defined in Eq. (11) (m/kg)</td>
</tr>
<tr>
<td>$C$</td>
<td>a coefficient defined in Eq. (7) (kg/m$^3$)</td>
</tr>
<tr>
<td>$C_D$</td>
<td>dextran concentration in original suspension (kg/m$^3$)</td>
</tr>
<tr>
<td>$C'_D$</td>
<td>dextran concentration contributed to cake formation (kg/m$^3$)</td>
</tr>
<tr>
<td>$C_p$</td>
<td>dextran concentration in filtrate (kg/m$^3$)</td>
</tr>
<tr>
<td>$C_Y$</td>
<td>yeast concentration in original suspension (kg/m$^3$)</td>
</tr>
<tr>
<td>$n$</td>
<td>cake compressibility defined in Eq. (11) (-)</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>filtration pressure (N/m$^2$)</td>
</tr>
<tr>
<td>$q$</td>
<td>filtration flux (m$^3$/m$^2$ s)</td>
</tr>
<tr>
<td>$R_c$</td>
<td>cake filtration resistance (m$^{-1}$)</td>
</tr>
<tr>
<td>$R_f$</td>
<td>filtration resistance due to membrane internal fouling (m$^{-1}$)</td>
</tr>
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<td>$R_m$</td>
<td>filtration resistance of filter medium (m$^{-1}$)</td>
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<tr>
<td>$R_{ref}$</td>
<td>dextran rejection defined in Eq. (8) (-)</td>
</tr>
<tr>
<td>$\alpha_{av}$</td>
<td>average specific filtration resistance (m/kg)</td>
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<td>$\mu$</td>
<td>viscosity of fluid (kg/s m)</td>
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References


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