Modeling the Influence of Slurry Concentration on *Saccharomyces cerevisiae* Cake Porosity and Resistance During Microfiltration

Manuel Mota
IBB, Institute for Biotechnology and Bioengineering, Centro de Eng. Biológica, University of Minho, 4710-057 Braga, Portugal

Michael C. Flickinger
Dept. of Chemical and Biomolecular Engineering, Golden LEAF Biomanufacturing Training and Education Center, North Carolina State University, Raleigh, NC 27695

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Filtration of an isotonic suspension of baker's yeast through a 0.45-μm membrane was studied at two different pressures, 40 and 80 kPa, for yeast concentrations ranging from 0.14 to 51 kg/m^3 (dry weight). For a yeast volume fraction above 0.06 (∼21.8 kg/m^3), the porosity of the yeast cake is less dependent on the suspension concentration. For highly diluted suspensions, the specific cake resistance approaches a minimum that depends on the filtration pressure. Correlation functions of cake porosity and specific cake resistance were obtained for the concentration range investigated showing that the Kozeny–Carman coefficient increases when the applied pressure increases. Both filtration pressure and slurry concentration can be process controlled. In the range of moderate yeast concentration, the filtrate flux may be increased by manipulating the filtration pressure and the slurry concentration, thereby improving the overall process efficiency. The complex behavior of yeast cakes at high slurry concentration can be described by a conventional model as long as part of yeast cells are assumed to form aggregates, which behave as single bigger particles. The aggregation effect may be accounted for using a binary mixture model. © 2012 American Institute of Chemical Engineers *Biotechnol. Prog.*, 28: 1534–1541, 2012
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Introduction

Filtration of yeast cells from a liquid phase is widely practiced in biopharmaceutical biotechnology, food, beverage, chemical industries, and biomedicine.[1] Yeast suspensions have been studied over a broad range of suspended solid concentrations, and numerous publications in the literature investigate the relationship between yeast slurry concentrations with specific cake resistance without investigating the fundamentals of cake porosity. The wide diversity of solid–liquid phase properties of yeast suspensions implies that a general model describing cake resistance vs. solid concentration is hardly applicable. This is especially true because yeast is compressible, differ in shape, and can aggregate. Moreover, yeast properties are dependent on the cultivation conditions.[2–8] Microscopic measurements show a ratio of maximal to minimal cell axis of ∼1.20–1.33 to 1.465–2.064.[3,4,6,7] Accurate data on the axis ratio of yeast aggregates or flocs have rarely been reported.[9] Therefore, systematization of available experimental data over a broad yeast concentration range becomes extremely difficult. This system approach is critical for accurately predicting microfiltration processes.

The purpose of this work is to study the experimental dependence of cake resistance in dead-end filtration experiments over a wide range of yeast concentrations and to develop a correlation model useful to improve filtration efficiency.

Correspondence concerning this article should be addressed to M. C. Flickinger at michael_flickinger@ncsu.edu.

Background

Yeast suspensions

Interest in yeast filtration is increasing steadily due not only to the growing volume of bakers' yeast and alcoholic beverages production but also to the applications of yeast cells as an expression system for biopharmaceutical production. A bibliographic analysis performed within ISI Web of Knowledge database on "yeast filtration" or "yeast microfiltration" shows that in the 5 last years more than 500 publications were devoted to different aspects of yeast filtration. Furthermore, an enlarged overview of publications encompassing the last 10 years concerning *Saccharomyces cerevisiae* filtration and the influence of slurry concentration on yeast microfiltration yielded over 100 articles. The high number of retrieved works and the limited space for bibliographic references led the authors to mention only those references that are related to our present work.

S. cerevisiae cells have been used in many filtration experiments as resuspended active cells (unwashed or washed), inactive, and cultivated cells.[6,10–14] For instance, Schluep and Widmer[3] investigated commercially available

baker's yeast, *S. cerevisiae* (average yeast size 5.35 μm), resuspended in citrate buffer at pH 6 containing sodium chloride (6 g/L) and sodium azide (0.3 g/L).[3] Part of their experiments were performed with cultivated *S. cerevisiae* S 288 C (yeast size 3.77 μm). After harvesting, 0.3 g/L sodium azide was added to inactivate the suspension. Newtonian behavior was established for cell volume concentrations up to 10%. With increasing transmembrane microfiltration pressure, the specific filter cake resistance approached the specific resistance measured for dead-end filtration. In contrast, active dry yeast resuspended in deionized water was used in multiple studies.[4,6,15–17] Other investigators used cultivated yeast cells, washed, and dispersed in isotonic saline (0.9% NaCl) solution.[18,19] Depending on the yeast technology, yeast concentrations during microfiltration vary over a wide range from 0.022 to 120 g/L[5,6,12,16–20] and ~0.14 to 13 vol %.[3,8,15] Some articles mention the use of a wide range of yeast concentrations but present results only for selected yeast concentration values thereby not allowing us to obtain a widely applicable correlation.

On the basis of the above data, we chose a working concentration range for yeast suspensions between 0.14 and 51 g/L (dry weight). The highest concentration is below the critical yeast concentration of 70.4 g/L, at which, according to Klein et al.,[21] the slurry viscosity begins increasing exponentially thereby starting a structuring phenomenon. Moreover, Zhang et al.[5] investigated the factors affecting membrane fouling occurring in filtration of *S. cerevisiae* through a ceramic filter inside a bioreactor. The operation was conducted at a maximum cell concentration of 60 g/L, which was considered as a suitable and operable concentration in membrane-based culture systems. These systems could withstand cell concentrations higher than 200 g/L of cell dry weight, at the expense of less filtration efficiency.

Yeast filtration

The filtration law and cake hydraulic resistance depend on the physical and chemical properties of the yeast suspension and on the filtration regime. Cake properties in dead-end filtration are best studied at constant pressure, but when the yeast suspension is moving tangentially to the filter medium the cake forms during cross-flow microfiltration, where the operating pressure increases gradually. Nevertheless, in both filtration modes, a similar theoretical background is used to describe cake properties.[3,6,7] According to Redkar and Davis[15] and to Tanaka et al.,[10] the initial transient flux decline in the cross-flow mode follows the dead-end filtration law. Numerous yeast microfiltration experiments performed on membranes of pore size less than 1 μm confirm the cake filtration mode and the possibility of using the Carman–Kozeny equation to model the cake permeability/hydraulic resistance.[4,6–8,21–24]

A relationship between the filtrate flux and the biomass concentration was observed for yeast and bacteria in the work of Park et al.[25] For the microfiltration of a *Bacillus polymyxa* broth through a membrane, Nagata et al.[26] reported a decline in the permeability coefficient with the increase in cell concentration. For baker's yeast, it was determined that steady-state cross-flow filtration flux is a function of $c^{-0.5}$, according to Shimizu et al.,[27] where c is the yeast concentration in kg/m^3. In turn, Schluep and Widmer[3] found that the specific cake resistance for *S. cerevisiae* remained constant with the increase in the yeast volume fraction ϕ in the suspension. The cake permeability vs. yeast volume fraction is twofold smaller for small flocs than reported for fully flocculated yeast.[24]

More recently, Xu et al.[28] developed a mathematical model to describe cake filtration for both Newtonian and non-Newtonian fluids, in either steady or unsteady filtration stages, which was not specific for biological suspensions.

This brief overview shows the complex nature of the cake resistance, even in the case of similar suspended matter. The functional dependence of specific cake resistance on solid mass fraction may be represented by a generalized empirical relationship written in the form[29]

$$\alpha(c_m) = a_0 + b_0(c_m)^k \exp(d_0 c_m), \tag{1}$$

where a_0, b_0, d_0, and k are empirical coefficients that must be determined through the experimental determination of the dependence of α vs. c_m. After conducting the data fitting, it is often possible to assume that some coefficients are zero, leading to a simplified expression.

The above-mentioned articles paid attention to the dependence of the permeation flux on transmembrane pressure in dead-end and cross-flow filtration. However, the interrelation of yeast concentration, cake porosity, and specific resistance was not considered in any of these studies. Yeast concentration, physicochemical characteristics of suspensions, filter media type, and pressure values vary from article to article, thereby not allowing generalizing dependences and conclusions. Moreover, attention has been mostly paid to the effect of filtration pressure rather than to slurry concentration and to the effect of yeast concentration on flocculation. This leads to a local or restricted interpretation of the results and does not permit experimental data to be utilized to generate a useful predictive model of specific cake resistance vs. suspension concentration.

Cake filtration law

For cake filtration, the relation between the filtrate flux J and the specific filtrate volume may be written as follows:

$$J = dq/dt = \frac{\Delta p}{\mu[\alpha(c_m) \cdot x_m(c_m) q + R_m]}, \tag{2}$$

where q is a specific filtrate volume per unit of filtration area, m^3/m^2; t is the filtration time, s; Δp is the filtration pressure, kPa; μ is the liquid viscosity, Pa s; α (c_m) is the specific cake mass resistance, m/kg; c_m is the solid mass fraction in suspension; $x_m(c_m)$ is the ratio of cake solid mass to the filtrate volume; and R_m is the filter medium (membrane) resistance, m^{-1}. In Eq. 2, at least two parameters, α and x_m, depend on slurry concentration. Inverting, integrating, and rearranging (2) lead to the linear solution (3)

$$t/q = Aq + B, \tag{3}$$

where $A = \mu \cdot \alpha \cdot x_m/(2\Delta p)$ and $B = \mu R_m/\Delta p$. The specific cake mass resistance α and R_m, the filter medium (membrane) resistance, may be determined using the linear function (3) as long as the dependence q vs. t is measured at constant Δp.

The behavior of specific cake resistance with increasing slurry concentration would reflect changes in the filter cake structure[7]

$$\alpha = \frac{36K \cdot (1-\varepsilon)}{\rho_c \, d_p^2 \, \varepsilon^3}, \quad (4)$$

where ρ_c is the solid-phase density, ε is the cake porosity, and d_p is the particle diameter. $K = K_0\tau^2$ is the Kozeny–Carman coefficient that includes a pore tortuosity τ and a coefficient K_0 related to pore (particle) shape and dependent on porosity.[7,23,30] For granular beds, K is assumed to be constant and around $K = 4.2$–5.0, because of the relatively narrow range of values for granular bed porosity. However, in the generalized case, this parameter should be considered a variable, especially when the yeast cake is compressible, or when there are cake structure rearrangements during microfiltration. The specific cake mass resistance and cake permeability, k, are related as $\alpha = k\rho_c(1-\varepsilon)$. For the estimation of specific cake resistance, the Kozeny–Carman relationship is widely used in the form $\alpha = 180(1-\varepsilon)/(\rho_c \, d_p^2 \, \varepsilon^3)$. A coefficient 180 is often used for granular bed packing and corresponds to $K = 5$. If we assume that the particle size is constant, meaning that no cell aggregation occurs during the filtration, the change in the specific cake resistance will correspond to a porosity variation, related with changes in packing density.

In this work, a novel assumption is proposed. We propose that the increasing particle concentration in the filtration cake may lead to particle aggregation so that the cake formed might be composed both of aggregates and individual particles (yeast cells). Depending upon the aggregate structure, the effect of aggregation on the filtration efficiency may be accounted by using the effective particle size (based on aggregate size). In this approach, the cake is considered as a binary packing consisting of a mixture of aggregates and single particles. This assumption will be studied and validated with our own experimental results as well as with several studies from the literature.

Materials and Methods

Dead-end filtration is the standard procedure to estimate specific cake resistance, and this method was adopted in this work. Commercially available *S. cerevisiae* (baker's yeast, DSM) was resuspended in an isotonic solution (0.9% NaCl solution in deionized water) and was used as the experimental model. Baker's yeast cells presented a narrow-size distribution, with a measured average cell size of 5.8 μm and a spheroid shape with axis aspect ratio of 1.4. The range of yeast slurry concentration studied, c, varied from 0.14 up to 51 kg/m^3. This range covers the yeast concentration range usually present in a wide variety of biotechnological processes. As the yeast volume fraction in the slurry ϕ is more representative for cake analysis than the mass-volume concentration c (see Ref. 8), the volume fraction ϕ will be used from now on.

To see whether there is a marked difference on viscosity, a set of experiments was conducted to measure viscosity of an isotonic solution (0.9% of NaCl in deionized water), of fresh yeast culture medium with 30g/L glucose and of the same spent yeast culture medium, after removal of the grown cells. Differences in viscosity were not found significant, as the biggest relative difference between the viscosity assays done in triplicate stayed below 3%. Therefore, the viscosity of the liquid phase can be considered, for all cases, to be 1.01×10^{-3} Pa s.

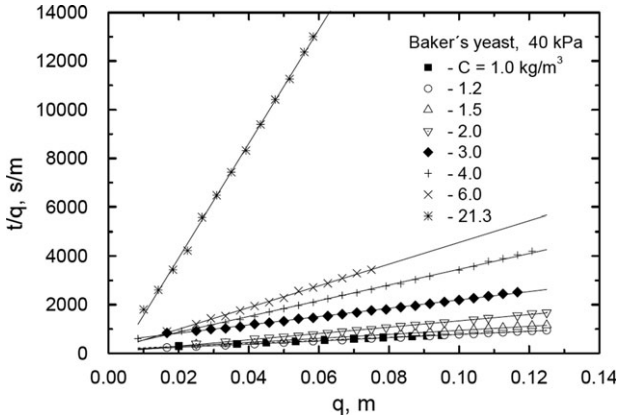

Figure 1. Dependence of t/q on q for different yeast concentration c (kg/m^3).

The applied filtration pressure is 40 kPa.

The yeast filtration performance as a function of slurry concentration was studied at 20°C using a cylindrical vessel of 32-mm inner diameter as a filter unit with a supported Gelman membrane (pore size 0.45 μm) at the bottom. The filtration pressure for all slurry experiments was constant during the filtration test provided by a vacuum pump controlled by a manometer. The yeast filtration performance was studied at filtration pressures of 40 and 80 kPa in all batch experiments. These values of filtration pressure were chosen according to the experimental conditions reported in the above-mentioned publications for *S. cerevisiae*. The value of the critical transmembrane pressure, when further pressure increase does not affect the permeate flux, was also taken into account.[22]

The specific cake mass resistance α was determined using the linear function (3) and the dependence of q vs. t was measured at different slurry concentrations. The nonlinearity on the initial filtration stage was omitted for two reasons. On one hand, this part concerns a rather small concentration time, covering less than 10% of the overall filtration time. On the other hand, at a filtration time close to 0, the number of cells settled onto the membrane is negligible, taking into account the purpose of this work. A typical plot of the linear part of the dependence of t/q on q for $\Delta p = 40$ kPa is shown in Figure 1. Similar linear dependences were obtained for 80 kPa. In both operating pressures, the correlation coefficient of the fitting lines was higher than 0.95. The viscosity of the liquid phase was 1.01×10^{-3} Pa s. The measured hydraulic resistance of the Gelman membrane R_m was 1.2×10^{10} m^{-1}. The linear slope corresponds to coefficient A of Eq. 3. Therefore, if the parameter x_m, the ratio of cake solid mass to the filtrate volume is known, the specific cake resistance α can be obtained.

The ratio x_m of the cake solid mass to the filtrate volume was calculated according to Aiba et al.[31]

$$x_m = c_m\rho/(1 - mc_m), \quad (5)$$

where c_m is the solid mass fraction in the slurry, kg/kg; ρ is the liquid-phase density, kg/m^3; and m is the ratio of wet cake mass to the solid mass in the cake. The parameter m may be represented in the form $m = 1/c_{mc}$, where c_{mc} is the maximum solid mass fraction in the cake. The small difference between the cell density (in the isotonic solution) and the solution density allows us to assume that $c_m \approx \phi$.[10,27]

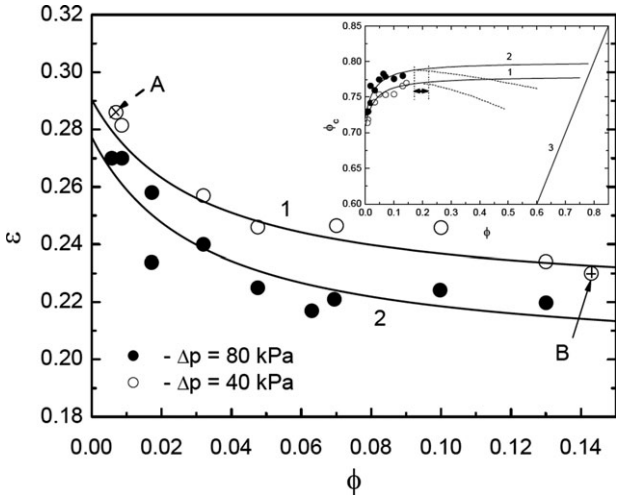

Figure 2. Dependence of the cake porosity ε and density $\phi_c = 1 - \varepsilon$ (inset) on ϕ for filtration pressures 40 and 80 kPa.

Points—experimental data; curves 1 and 2—approximation by Eq. 6; 3—diagonal. Arrows: A—Value from Geissler and Werner.[32] B: Adapted from Ref. 23.

Results and Discussion

Cake porosity

Cake porosity was calculated from m (see Eq. 5), by assuming $c_{mc} \approx \phi_c$, the porosity is $\varepsilon = 1 - \phi_c = 1 - 1/m$, where ϕ_c is the solid-phase (yeast) volume fraction in the cake. Results experimentally obtained for cake porosity are shown in Figure 2 together with values from the literature. As may be seen from the graph, the cake porosity depends both on yeast concentration and on filtration pressure. The cake packing density increases with an increase in slurry concentration ϕ. Two regions for the cake porosity behavior are seen in Figure 2: a region of intensive decrease in porosity, corresponding to low slurry concentrations, and a region of quasi-constant porosity when $\phi > 0.06$–0.08.

For both filtration pressures, the dependence of ε on ϕ is described within the experimental range by the following fitting function

$$\varepsilon = 0.23 \text{ arctg}\left(\frac{b_1}{\phi + 0.03}\right) + c_1, \qquad (6)$$

where for $\Delta p = 40$ kPa, $b_1 = 0.00905$ and $c_1 = 0.22$; for 80 kPa $b_1 = 0.0105$ and $c_1 = 0.2$. The application of other fitting functions, for instance exponential, leads to significant deviations in the further modeling of α as expressed by Eq. 1, for $\phi > 0.02$. The cake is more compact with a higher filtration pressure due to the cake compressibility. Cake compressibility was determined from the cake resistance values as $\alpha = \alpha'(\Delta p)^n$, where α' is a coefficient and n is a compressibility index. For the filtration pressures used in this work, in the range of 40–80 kPa, the average value of the observed compressibility index $n = 0.7$ coincides with those measured for baker's yeast[27] with values reported earlier by our group.[7]

The porosity determined experimentally in this work coincides with the data calculated assuming a spheroidal packing. It is also in agreement with the porosities reported in various studies with yeast cakes.[7,10,18,22,23,33] The dependence of cake porosity on slurry concentration can be explained by the increasing number of cell aggregates with increasing ϕ. These aggregates or flocs may be considered as secondary larger particles (with an effective particle size close to the aggregate size) incorporated in the cake. In this way, the cake can be analyzed as a binary particle mixed bed. The aggregate stability in the cake depends on the aggregate packing density that, in turn, depends on the number of cells in the aggregate (aggregate size).[34] For $\phi > 0.06$–0.08, a further increase in the aggregate size leads to a reduction of its strength. Also, stabilization of the cake packing density and porosity may be expected. For example, for yeast flocs of average size 1,750 μm, the porosity was 0.9763.[9] At high slurry concentration, a structuring phenomenon may lead to a reduced cake packing density ϕ_c.

The upper concentration limit used in the present experiments (51 g/L) is similar to that of a structured suspension. Using cross-flow microfiltration, Keskinler et al.[14] determined that, nonliving yeast suspensions have a pseudo-gel concentration on the membrane surface of 45 g/L ($\phi \approx 0.12$). Also, a rheological investigation of a flocculating yeast slurry used by Klein et al.[21] reported a critical yeast concentration of 73 g/L. Redkar and Davis[15] determined for yeast cross-flow filtration through a tubular membrane a critical packing density in the range of 0.22–0.29, depending on the filtration membrane properties. Hence, in the range marked by arrows in Figure 2 inset, structural changes in yeast suspension are expected with further decrease in ϕ_c (dashed curves), which is, in any case, far beyond the experimental range used in this work.

Specific cake resistance

The yeast specific cake resistance demonstrates the dependence on both filtration pressure and slurry concentration, as shown in Figure 3 (points marked with crosses were obtained from McCarthy et al.[6]). Similar values of α were measured by other investigators, these results being coincident with the ones presented in this work.[4,10,18,22,35,36] An increase of α is clearly observed, when the values of ϕ increase. However, this dependence is complex and

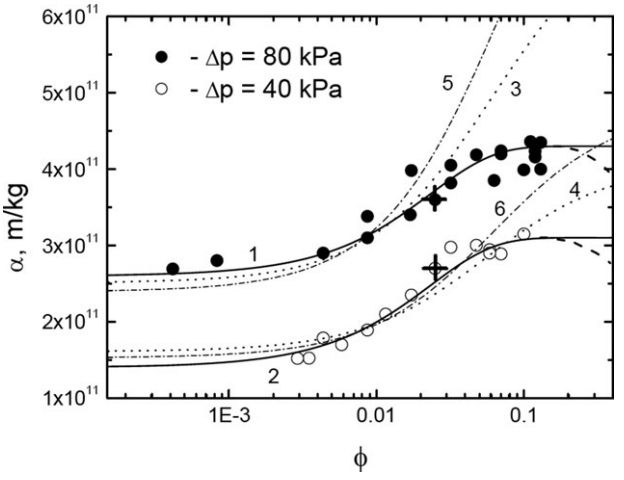

Figure 3. Dependence of the yeast specific cake resistance α on slurry concentration ϕ.

The points are experimental data, where (+) values were adapted from Ref. 6. Curves 1 and 2 correspond to the fitting function (7) obtained from formula (1), whereas curves 3 and 4 are calculated by Eqs. 4 and 6. Curves 5 and 6 are calculated by Eqs. 4 and 6 assuming tortuosity variation.

experimental data were fitted using two different methods (Figure 3):

(1). Fitting experimental data by formula (1), resulting in curves 1 and 2.

(2). Application of Eq. 4 incorporating the fitting function (6), giving curves 3 and 4.

For the full range of the investigated slurry concentration, Eq. 1 may be represented as

$$\alpha = a_0 - 1.7 \times 10^{11} \exp(-43 \cdot \phi) \qquad (7)$$

with $a_0 = 3.2 \times 10^{11}$ and 4.3×10^{11} m/kg for $\Delta p = 40$ and 80 kPa, respectively (Figure 3, curves 1 and 2). When $\phi \rightarrow 0$, a condition corresponding to infinite dilution (negligible solid fraction), according to Eq. 7, α_0 values are 1.5×10^{11} and 2.6×10^{11} m/kg, respectively. In this case, we can assume that each cell is able to find its way freely when it is settling, giving rise to the highest possible packing density. As is well known, for spheroid particles, the hexagonal close packing yields the highest average packing density (0.74) leading to a porosity of $1-0.74 = 0.26$. Moreover, the body-centered cubic packing gives a porosity of 0.32. By calculating the average mean between the hexagonal packing and the body-centered packing, we may assume that at infinite dilution the average cake porosity is 0.3. With an experimental yeast's cell size of 5.8 μm, we obtain from Eq. 4 at $K_0 \tau^2 = 5$ (corresponding to $\alpha = 180 (1 - \varepsilon)/(\rho_c d_p^2 \varepsilon^3)$) $\alpha_0 = 1.28 \times 10^{11}$ m/kg and at $\tau^2 = 1/\varepsilon$, $\alpha_0 = 2.13 \times 10^{11}$ m/kg.[37] Estimated and experimental values are in good agreement.

Equation 7 agrees with the experimental data. It is assumed that the volume of filtered slurry is large enough to form a cake on the membrane even for small ϕ. Coefficient α_0 corresponds to the specific cake resistance for an infinitely diluted suspension. It depends on the filtration pressure and has a significant contribution for the fitting procedure. Therefore, the boundary condition $\alpha_0 > 0$ is important for modeling a long run filtration of a diluted suspension.

Application of Eq. 4 with the incorporated fitting function (6) is useful for the calculation of the permeability k and the Kozeny–Carman coefficient K dependences on concentration and filtration pressure (curves 3 and 4, Figure 3). The following average values of the Kozeny–Carman coefficient were obtained for low and moderate yeast concentration: $\Delta p = 40$ kPa, $36 \cdot K = 204$, hence, $K \approx 5.67$; $\Delta p = 80$ kPa, $36 \cdot K = 272$, and $K \approx 7.55$.[7] As can be seen, the coefficient K has a tendency to increase when the applied filtration pressure increases. In the range of moderate concentrations, model (4) deviates from the α experimental values. One of the reasons for the observed effect is the tortuosity dependence on cake porosity.[38] Conventionally, the relationship between tortuosity τ and ε is represented by $\tau = 1/\varepsilon^n$, where $n = 0.4$–0.5 for spherical particles. In this case, the specific cake resistance (4) takes the form $\alpha = 72 \cdot (1 - \varepsilon)/(\rho_c d_p^2 \varepsilon^{3+2n})$ (K_0 is assumed to be 2.0) and is shown in Figure 3 as curves 5 ($n = 0.5$) and 6 ($n = 0.4$). It is interesting to speculate that a large n value for a higher filtration pressure might be related with the compression of yeast cells that block some pores. If this happens, then the flow pathway increases, and the relation τ vs. ε is stronger. Nevertheless, starting from moderate concentrations, this model overestimates the cake resistance for $\phi > 0.01$.

The results displayed in Figure 2 point out that porosities, for both pressures, stay below 0.26 between $\phi = 0.02$ and 0.14. As the cells used in this experimentation belong to the same population and they are compressible the same way. As 0.26 is the lowest possible porosity for a homogeneous spheroid population, and as there was no significant difference in viscosity, one must admit that it is likely that the cell population is not homogeneous in size.

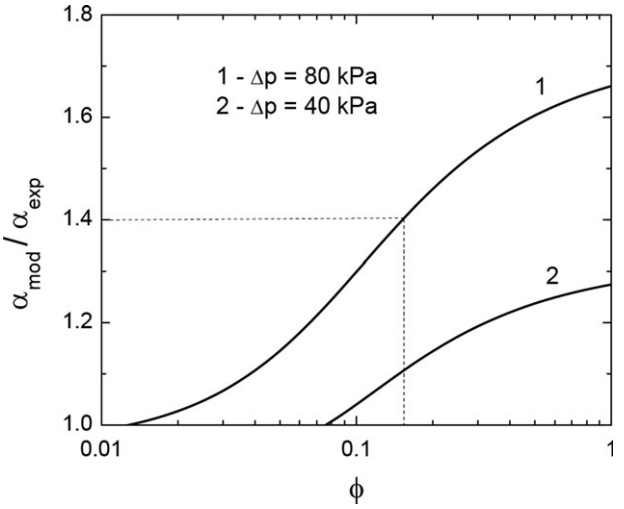

Figure 4. Deviation of predicted α_{mod} from experimental α_{exp} vs. concentration ϕ.

The dashed lines correspond to the investigated range of concentration, where maximum deviation from experiment was $\alpha_{mod}/\alpha_{exp} \approx 1.4$.

The gradual increase in concentration enlarges the gap between predicted α_{mod} (Eqs. 4 and 6) and the lower measured α_{exp} (Eq. 7) specific cake resistance (Figure 4). This observation leads us to speculate that lower α_{exp} can be explained as follows.

Previous work showed that, whenever a binary or ternary size particle population is present, the porosity can be drastically reduced, depending on the volume ratio of each fraction as well as on the size ratio.[4,37,38] The probability of cell aggregation increases with the suspension concentration. In this case, some aggregates remain intact after incorporation into the cake, even more so when they withstand compression (see Figure 5). Simulations of diffusion-limited cluster aggregation (DLCA) and gelation were done over a broad range of concentrations.[39] Results show that DLCA of particles at low volume fractions ($\phi < 0.05$) occurs initially by collisions between clusters that are on average well separated. Close to the gel point, the clusters are highly interpenetrated and the aggregation may be described as a percolation process. The transition between the flocculation regime and the percolation regime leads to a change of the structure and of the aggregate size distribution. The effect of the interaction energy on floc structure was modeled by Cohen,[34] who found that the influence of a dimensionless energy of particle interaction on floc structure decreases with the decrease in the aggregate size. Moreover, relatively small aggregates (with particle number $N \leq 12$) have a high probability to build a dense packing.

Aggregation and flocculation show that flocs have a fractal structure, and their porosity is defined, in general, as $\varepsilon \propto 1 - (N)^{\frac{d_F - 3}{d_F}}$, where d_F is the floc fractal dimension.[38–40] For instance, it was found that for an activated sludge $d_F = 2$, hence, $\varepsilon \propto 1 - N^{-0.5}$.[40] In the work of Li and Ganczarczyk,[41] the upper limit of d_F is 2.8; Logan and Wilkinson[9] give for cultivated flocculating yeast fractal

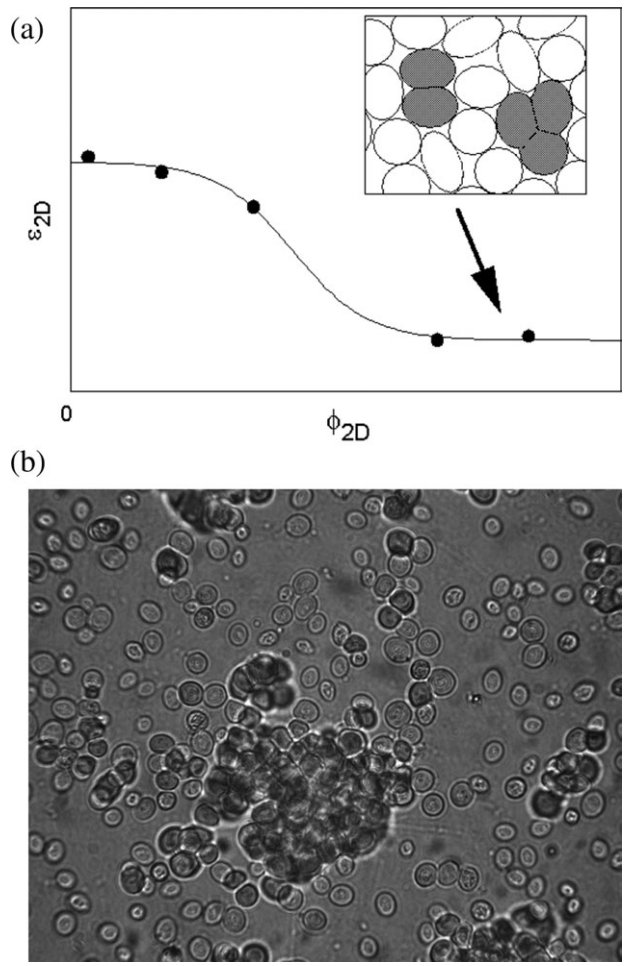

Figure 5. (a) Sketch of two-dimensional (2D) cake build up simulation.[8]

2D porosity ε_{2D} vs. 2D concentration ϕ_{2D} (curve) and sketch of overlapped cells (gray) distributed within the cake in the region of packing porosity marked by arrow. (b) Micrograph of the yeast clusters at ×1,000 magnitude: the filtration cake was resuspended in isotonic solution and stirred for 5 min at 100 rpm before being observed microscopically.

values ~2.66–2.86. The simulation of aggregation confirms that the fractal dimension of aggregates and, hence, their compactness increases with the increase of the suspension concentration.[42]

Summarizing, in our case, cake cell aggregates are likely to occur and may be considered, in a first approach, as a quasi-particle of diameter d_{ps} with a volume equal to the total aggregate volume $d_{ps} = N^{1/3}d_p$, where N is the cell number in the aggregate. The simulation reported by Mota et al.[8] confirms this assumption, and the results are shown in Figure 5a. In the concave part of the curve, marked by an arrow, a significant increase in the probability of cell aggregation was observed. Simulated and experimental profiles of the dependence ε on ϕ are quite similar. We may therefore consider that aggregated particles may function as bigger particles, and that a binary packing model can be assumed.[43,44]

In Figure 5b, the existence of clusters of yeast cells is clearly shown, demonstrating the adequacy of the assumption previously made. This is micrograph of a resuspended yeast filtration cake subjected to 100 rpm stirring for 5 min. Even with these stirring conditions, aggregates remained stable.

The binary packing model considers the cake as a mixture of two different size particles d_P and $d_{ps} = N^{1/3}d_p$, being the average particle diameter in the cake

$$d_{av} = \{x_{ps}/(N^{1/3}d_p) + (1 - x_{ps})/d_p\}^{-1}, \qquad (8)$$

where x_{ps} is the fraction of N-agglomerated cells in the mixture. For simplicity, as a first approximation, we shall ignore the aggregate porosity. Yeast cells in aggregates display a denser packing than flocs, and its fractal dimension approaches 3.0. As can be seen from Figure 6a, a value for d_F in the range 2.7–2.8 is reasonable for yeast aggregates, when N is above 7.0. In Figure 6a, the dashed line corresponds to the cake porosity at $\phi \sim 0.06$–0.16.

If the aggregation effect includes part of the dispersed phase for $\phi \sim 0.06$–0.16, an overall porosity ε stabilization may be observed because of the interplay of the following factors (this discussion is limited to $\phi \sim 0.06$–0.16):

1. The probability of obtaining a dense-packed floc/aggregate decreases with an increase in concentration.[34] A distribution of flocs by size, density, and porosity will occur.

2. The consideration of aggregates as large particles means that packing porosity decreases with an increase of d_{ps}, although a simultaneous increase in d_{av} leads to a slowdown in the increase of cake resistance.

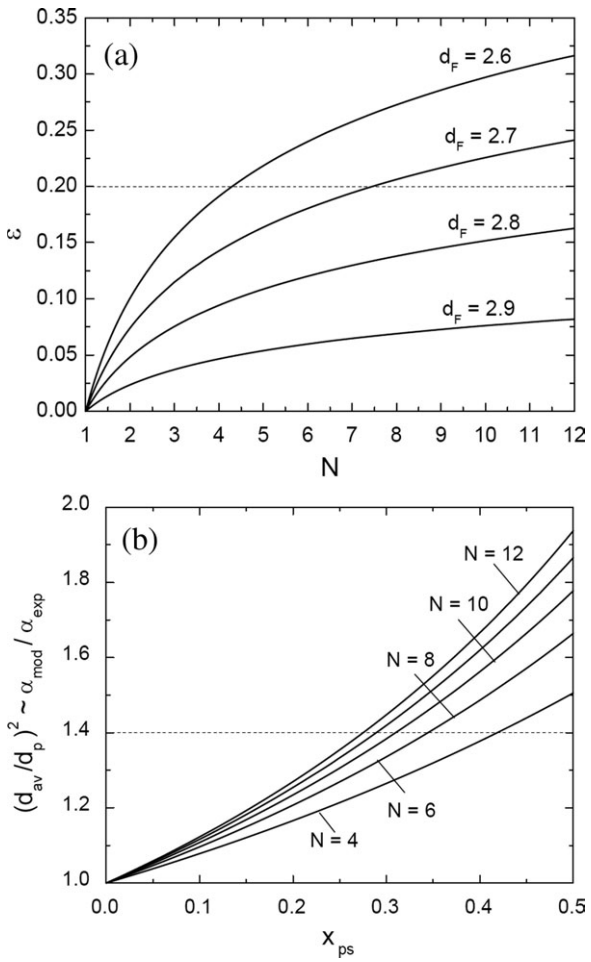

Figure 6. Role of aggregation in specific cake resistance.

(a) Effect of aggregate's fractal dimension and N on aggregate porosity. (b) Dependence of $(d_{av}/d_p)^2 \sim \alpha_{mod}/\alpha_{exp}$ on the volume fraction of aggregates in cake x_{ps} and degree of aggregation N.

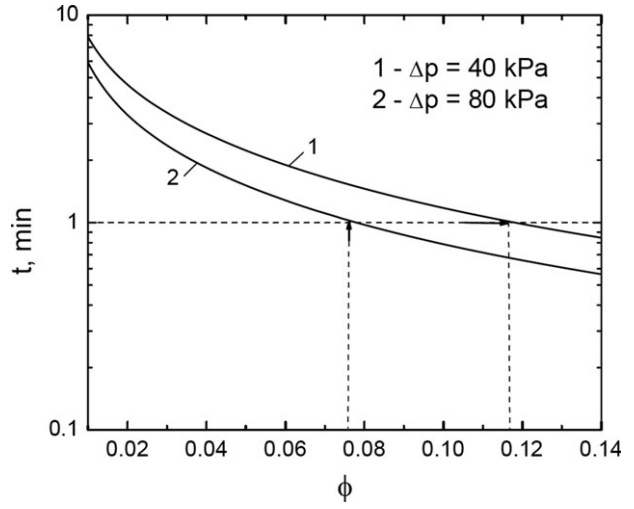

Figure 7. Filtration time t needed to obtain 1-mm thickness yeast cake on the Gelman membrane (0.45 μm).

1—Filtration pressure 40 kPa and 2—filtration pressure 80 kPa.

The dependence of $(d_{av}/d_p)^2 \sim \alpha_{mod}/\alpha_{exp}$ on the volume fraction of aggregates in cake x_{ps} and the degree of aggregation N are shown in Figure 6b, where the dashed line represents the $\alpha_{mod}/\alpha_{exp}$ values for $\phi \sim 0.14$. Estimated values are within the range of the observed cake resistance gap (see Figure 4). Nevertheless, the results and the assumptions indicate that the complex behavior of the yeast cake at a high slurry concentration can be described with the help of conventional binary or ternary particulate mixture.

Experimental results show the importance of specific cake resistance and concentration relationship on filtration. As an example, Figure 7 represents the filtration time t needed to obtain a 1-mm thickness yeast cake through a 0.45-μm membrane (Gelman), where a higher filtration pressure gives a lower filtration time.

Nevertheless, the reduced cake resistance in the more concentrated slurry ($\phi = 0.12$) led to the same filtration time t at half the pressure, leading to energy saving.

The study, reported here, examines the effect of yeast suspension feed concentration on filtration performance of a particular system in a wide range of concentration that we cannot find in previous works. Dependence of cake porosity and specific cake resistance, also, contain new information. Further research will be devoted to investigate the aggregation effect on yeast filtration and cake properties especially for high concentration slurries.

Conclusions

Filtration of a baker's yeast suspensions in an isotonic solution through a 0.45–μm membrane was studied for yeast concentrations in the range of 0.14–51 kg/m^3 and the filtration pressure values of 40 and 80 kPa. It was found that, for a yeast volume fraction above 0.06, the porosity of the yeast cake is less dependent on the suspension concentration. It was also verified that the specific cake resistance of highly diluted suspensions tends to a minimum, which is sensitive to filtration pressure.

The Kozeny–Carman coefficient in the specific cake resistance relationship increases with the increase of applied filtration pressure. This means that if a decrease in porosity is simultaneous with an increase in tortuosity of cake pores, the specific cake resistance may be affected because of its compression. Further investigation will be needed for highly compressible materials.

Both filtration pressure and slurry concentration can be controlled during yeast filtration operations. In the range of moderate yeast concentration, the manipulation of filtration pressure and slurry concentration helps reduce cake resistance, thereby increasing the filtrate flux. This may be a subject for further investigation for precise filtration control at very high cell concentrations. Amongst possible approaches of cake resistance reduction to be considered are as follows: (a) a shift to bidisperse particle-size distribution, using slurry predilution/thickening; (b) optimization of the aggregate and single yeast cell balance as well as the aggregates size[45]; or (c) application of filter aids.[44]

Interpretation of the experimental results in all concentrations investigated and comparison with conventional Kozeny–Carman model has not been discussed before in other publications. In particular, based on our results, the complex behavior of yeast cakes at high slurry concentration can be described by a conventional model as long as part of yeast cells are assumed to be aggregates, which behave as single larger particles. Because of the aggregation effect inside the cake, the complexity of filtration cake porosity and resistance subsystems increases. The models proposed in this work may be particularly useful for planning further experimental work and precise microfiltration control at very high yeast concentrations.

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Notation

c = mass-volume concentration, kg/m^3
c_m = solid mass fraction in suspension, –
d_F = fractal dimension, –
d_p = particle diameter, m
J = filtrate flux, m^3/(m^2 × s)
k = permeability, m^2
L_{dm} = cell aspect ratio, –
N = particle number, –
q = specific filtrate volume, m^3/m^2
R_m = filter medium (membrane) resistance, m^{-1}
τ = tortuosity, –
t = filtration time, s
x_m = ratio of solid mass in the cake to the filtrate volume, kg/m^3
α = specific cake mass resistance, m/kg
ε = porosity, –
Δp = filtration pressure, kPa
ϕ = solid volume fraction, –
μ = liquid viscosity, Pa s
ρ = liquid-phase density, kg/m^3
ρ_c = solid-phase density, kg/m^3

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