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Broth Dewatering in a Horizontal Electric Field

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ABSTRACT

Removal of water from fermentation broth by applying horizontal electric field was investigated using yeast as a model system. The effects of the operation conditions including the initial concentration of yeast in the broth, starting pH and electroconductivity of the broth, and the magnitude of electric field indexed by potential drop on liquid removal were examined, respectively. The magnitude of ζ-potential of yeast cell was determined as a function of pH and electroconductivity of the broth. The results indicated the dominating role of ζ-potential of yeast cell on the efficiency of the dewatering process. Compared with the dewatering process operated in a vertical electric field, this new method has advantages in terms of efficient discharge of gases generated at two electrodes and ease of maintaining and controlling of the apparatus. These make the dewatering process in horizontal electric field more suitable for large-scale solid–liquid separations.

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Key Words: Fermentation broth; Dewatering; Electric field; Electro-osmosis; Electrodewatering.

INTRODUCTION

Separation of microorganisms from bulk liquid is often the first step of downstream processing in fermentation industries. Being small in size, compressible and hydrophobic microorganisms present the challenges for the conventional filtration processes and contribute significantly to the overall cost of the processing.[1,2] The presence of microorganisms in the concentrated bulk liquid also greatly affects the subsequent crystallization, leading to unsatisfactory purity of the product. On the other hand, the disposal of wet fermentation broth without effective concentration results in not only the reduction of yield of extra-cellular products but also, and more importantly, the contamination of soil or underground water resources.

Electrodewatering is a newly developed technique based on the electroosmotic flow at the surface of solid particles. Electrodewatering occurs when a direct voltage is applied to a suspension of particles, which also leads to the transport of charged particles and associated counter ions toward electrodes of opposite polarity. Thus the electrodewatering process involves both electrophoresis of particles and electroosmotic flux of liquid, all of which has a major influence on the rate and the extent of dewatering.[3,4] With its proven advantages in terms of high efficiency, low energy consumption, and being free from the blocking of the filter media by sludge particles at high concentration, as observed in the conventional filtration,[5] electrodewatering has attracted growing attention. Great efforts have been directed to applying this technique to sludge dewatering,[6] phosphate clay dewatering,[7] mine tailings dewatering,[8] and soil consolidation.[9] Pilot scale equipment for sludge dewatering has also been developed.[6,10] For conventional electro-dewatering process, electric field is vertically applied. The main shortage of the apparatus of this kind is of low efficiency in the discharge of gases produced by electrolysis. Moreover, the design and operation of the mobile anode are not convenient, especially for large-scale operation. In our previous work on sludge dewatering, we developed an apparatus using horizontal electric field that was proven to possess the advantages of rapid gas discharging, simple structure, and ease of operation,[11] compared with those driven by vertical electric field.[12]

The present study is in the context of the development of the electrodewatering driven by horizontal electric field. In recognition of the significance of fermentation process, an essential process in the production of

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fine chemicals, we focused our attention on the liquid removal from fermentation broth. For the present study, we selected yeast as a model system to examine the effects of operation parameters on the efficiency of liquid removal. The ζ-potential of yeast cell was measured as a function of physiochemical properties of solution. The experimental results established a preliminary understanding of the process characteristics, as well as the application potential of this new electrodewatering technique.

EXPERIMENTAL

Materials

The dry yeast used in the experiments in the present study was *S. cerevisiae* produced by Danbaoli Fermentation Co. Ltd. (Guangdong, China), which was 4–5 μm in length and 3–4 μm in diameter. Prior to the dewatering operation, the yeast was reactivated in deionized water for 24 hours at room temperature, around 20°C.

Apparatus

The experimental system is shown in Fig. 1, in which the heart of the apparatus is the plexiglas dewatering cell. A carbon graphite plate was used as anode and a copper net as cathode, which was covered with cotton cloth as

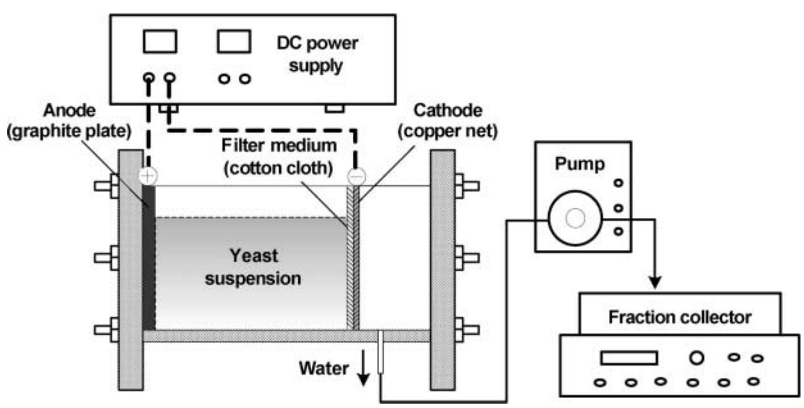

Figure 1. Experimental system of the electrodewatering.

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filter media. The cross-area of the loading compartment was 85 mm × 42 mm and the distance between two electrodes was 50 mm. In the experiments we used potential drop as an index of electric field strength.

Procedures

During a run, 130 mL fermentation broth containing 14.3% (wt%) yeast was firstly loaded into the sample compartment. Electric field was then applied and the electroosmotic flux out of the sample compartment was collected with fraction collector. Liquid removal efficiency, η, is calculated by Eq. (1):

$$\eta = \frac{M_w}{M_s(1 - C_0)} \times 100\% \qquad (1)$$

in which M_w is the weight of water collected, M_s is the weight of whole fermentation broth at beginning, and C_0 is the initial concentration of yeast, respectively.

Determination of ζ-Potential

The ζ-potential of yeast cell was measured with Zetaplus-Zeta Potential Analyzer (Brookhaven Instruments Co.). The dry yeast was first soaked in a given solution at room temperature for 24 hours. Then five samples were taken from the yeast suspension and subjected to measurement. The magnitude of zeta potential was thus determined as the average value of each measurement.

RESULTS AND DISCUSSION

Effect of Electric Field Configuration on Electrodewatering

Vertical electric field was extensively attempted in the present study of electrodewatering. The main shortage of the vertical electrodewatering equipment is the accumulation of gas beneath the top electrode. Moreover, the moving of water from anode to cathode would lead to a dry anode region and, consequently, an over consumption of direct voltage. Thus a mobile anode was commonly applied in the electrodewatering driven by a vertical electric field.[3−8] Focusing on these problems, we developed a new electrodewatering apparatus employing a horizontal electric field in order to facilitate the dissipation of gases produced at electrodes and keep the anode soaked in water

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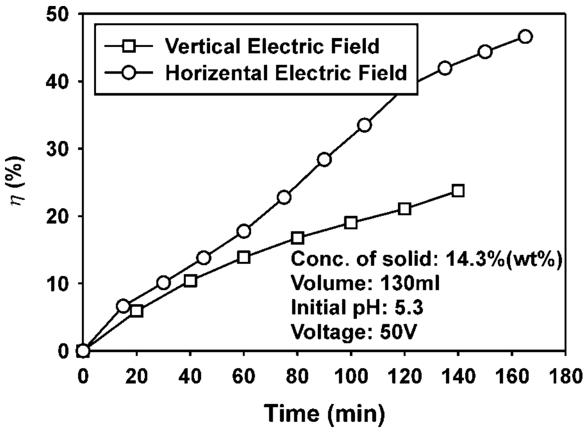

Figure 2. Time course of liquid removal at different electric field configuration.

during the dewatering process.[11] Figure 2 shows the electrodewatering results using the vertical apparatus developed in our previous study,[12] and the horizontal one, respectively. It could be concluded from the results shown by Fig. 2 that application of the horizontal electric field achieved a high water removal efficiency, compared with that in the vertical electric field. Thus the following experiments in the present study were performed in the horizontal electrodewatering apparatus.

Process Characteristics of Electrodewatering

Upon application of electric field, an electroosmotic flux of water from anode to cathode was observed, indicating that the surface of yeast cell was negatively charged. The mass flow rate, pH, and electroconductivity of electroosmotic flux as functions of time are shown in Fig. 3.

It is clearly indicated by Fig. 3 that pH of the electroosmotic flux out of cathode increased steadily at the early stage of dewatering and then decreased against operation time. In contrast, the magnitude of electroosmotic flux decreased steadily at the beginning stage, reached at its minimum when pH of the electroosmotic flux was at its maximum, and then started to increase. With the progress of electrodewatering, the magnitude of electroosmotic flux arrived at a relatively stable level. The electroconductivity, an index of the ionic strength of the electroosmotic flux, increased rapidly at the beginning stage and then reached a steady level.

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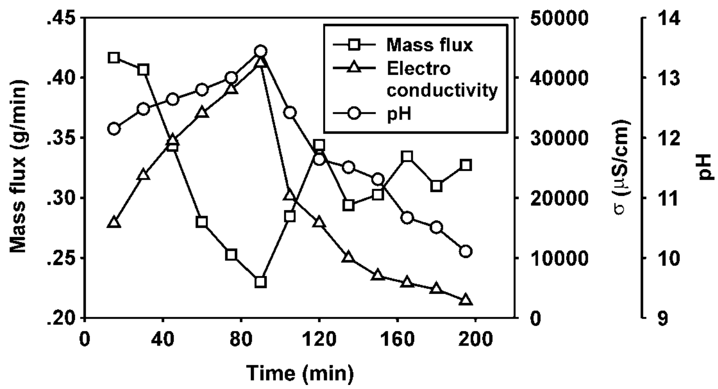

Figure 3. Time course of mass flux, pH, and electroconductivity of removed water.

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The application of electric field leads to the electrolysis of water at two electrodes, which contributes to an acidic pH in anode and an alkaline pH in cathode, respectively. At the beginning of the process, the OH^- generated at cathode was first carried out by electroosmotic flux, which caused the increase of pH of collected liquid at cathode. With the development of electrodewatering process, the alkaline pH near cathode will be neutralized by H^+ flux from anode, as shown in Fig. 3. Similar results were reported by Hamed and Bhadra in their study of electroremediation of contaminated soil.[13]

ζ-Potential of Yeast Cell

It is shown by Smoluchowsky equation[14] that the magnitude of electroosmotic flux is dominated by the magnitude of ζ-potential of solid particle. Thus we directed our attention to magnify ζ-potential of yeast cell surface so as to enhance the liquid removal from fermentation broth, especially at high concentration of yeast. Two sets of experiments were carried out, in which the first set was to examine effects of pH and electroconductivity of bulk liquid on the magnitude of ζ-potential of yeast. The second was to investigate if the chemicals used in the first set of experiments lead to irreversible changes of the surface of yeast cell.

During the experiment, 0.025 g dry yeast sample was soaked in 50 ml liquid containing given chemicals for 24 h. Then the yeast suspension was evenly divided into two parts. One part was subjected to the measurement of ζ-potential against the original liquid. The other part was washed with deionized water to

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Table 1. Zeta potential of yeast cell under different conditions.

	First set in given chemical solution			Second set in 1 mmol L^{-1} KCl		
	pH	Is (μS/cm)	ζ-potential (mV)	pH	Is (S/cm)	ζ-potential (mV)
Control	5.26	1440	−16.97	5.36	126	−19.13
KCl	5.31	4060	−4.17	5.66	128	−20.49
HCl	3.14	3740	−7.12	4.29	141	−18.67
NaOH	7.27	2720	−7.81	6.48	131	−20.48

remove the given chemicals and then subjected to the measurement of ζ-potential in 25 ml 0.001 mol L^{-1} KCl solution. The results are shown in Table 1.

It is shown by Table 1, in case of the three chemicals used in the present study, i.e., NaOH, HCl, and KCl, the addition of chemicals into the yeast suspension resulted in a significant reduction of the magnitude of ζ-potential. This is mainly due to the compression of the electrical double layer at the yeast cell surface in the presence of strong electrolyte that delivers ions in bulk solution. After washing with deionized water, the magnitude of ζ-potential of yeast approaches to that obtained in the controlled experiment, indicating that the addition of these strong electrolytes does not lead to the irreversible change of the surface property or composition of yeast cell.

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Effect of Initial pH of the Aqueous Phase of the Yeast Suspension on Liquid Removal

The initial pH of the yeast broth was about pH 5.3 at the concentration of 14.3% (wt%). The pH of the yeast suspension was adjusted with 1 mol L^{-1} HCl and 1 mol L^{-1} NaOH, and the electroconductivity of these two samples was about 3100 μs cm^{-1} and was then subjected to the electrodewatering. The results are shown in Fig. 4, which indicates that pH 5.34 is mostly suitable for electrodewatering of the yeast suspension.

Effect of Initial Electroconductivity of the Yeast Suspension on Liquid Removal

The initial electroconductivity of the yeast broth was 1400 μs cm^{-1} at the concentration of 14.3% (wt%). The electroconductivity was adjusted with 2 mol L^{-1} KCl before subjecting to the electrodewatering while the pH of

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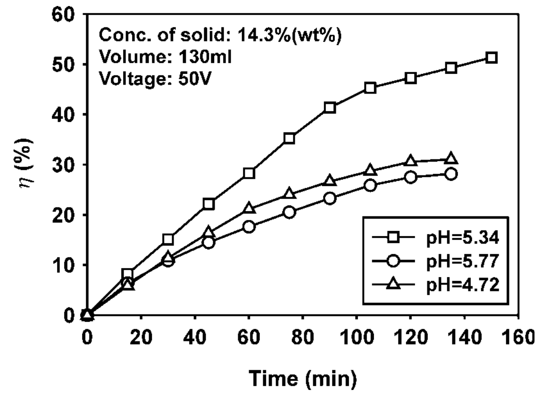

Figure 4. Time course of water removal at different initial pH of aqueous phase of yeast suspension.

the aqueous phase was maintained at pH 5.3. The results are shown in Fig. 5, which indicate that the increase of ionic strength resulted in a corresponding decrease in the liquid removal efficiency. This is due to the compression of the electrical double layer of the yeast cell at high salt concentration in the bulk solution, which reduces the magnitude of ζ-potential at the yeast cell surface and, consequently, the electroosmotic flux. It should be noted here that the electrolysis in anode may also lead to a pH change that reduces the zeta

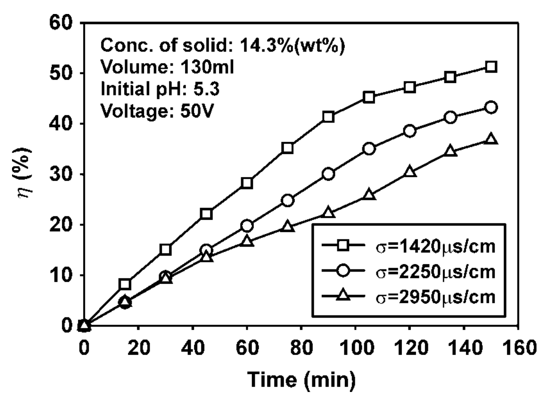

Figure 5. Time course of water removal at different initial electroconductivity of aqueous phase of yeast suspension.

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potential of yeast cell, and consequently, the reduction of electroosmotic flux. This will be included into the scope of our further study.

Effect of Starting Concentration of the Yeast Suspension on Liquid Removal

Liquid removal processes at different starting concentration of the yeast suspension are shown in Fig. 6. In the three cases of the present study, the best removal efficiency was obtained at 14.3% (wt%). As discussed in the introduction portion, electrodewatering includes mainly the electroosmosis which occurred at solid surface and the electrophoresis of solid particles, both of which lead to the accumulation and aggregation of solid particle along the dewatering process. The magnitude of electroosmotic flux is determined by the charge density of the particle surface. At low yeast concentration, e.g., 10.0% (wt%) in the present study, the surface charge density over the cross-area of the dewatering cell is low and thus contributes to lower magnitude of electroosmotic flux, compared with that obtained at high concentration. On the other hand, further increase in the yeast concentration in the suspension may lead to the overlap of the electrical double layer of the neighboring yeast cells which consequently results in the reduction of the average surface charge density over the cross-area of the dewatering cell. In this case, the estimation and calculation of the surface charge distribution should be based on the model developed by Rice and White.[15] The results shown in Fig. 6 indicate that there is a threshold of yeast concentration for the electrodewatering.

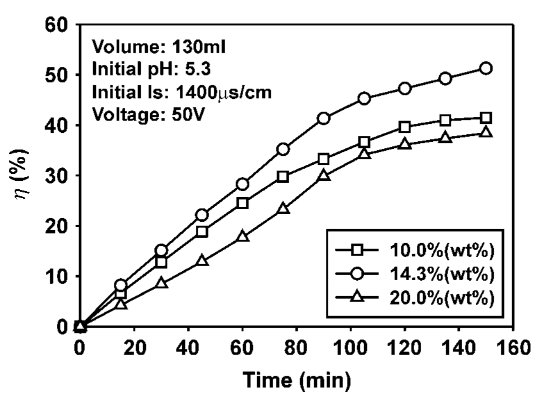

Figure 6. Time course of water removal at different initial yeast concentration.

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Effect of Applied Potential on Liquid Removal

The liquid removal at different applied voltage is shown in Fig. 7. The increase in the magnitude of the applied potential results in an increase in the magnitude of electroosmotic flux, and consequently, the increase of the overall liquid removal. This can also be predicted by Smoluchowsky equation.[14]

Discussion

At present, solid–liquid separation, a fundamental unit operation in fermentation industry, is mainly achieved by centrifuge filtration or press filtration. The centrifuge filtration can be continuously operated at an expected and reproducible efficiency. However, the main disadvantage is that it is energy consuming. The press filtration, though suitable for large-scale separation, is of low separation efficiency that may lead to unsatisfactory recovery of extra-cellular products in the bulk broth. The electrodewatering method, which is based on the electroosmosis at the surface of solid particles, has been proved to be effective in removing the vicinal water and the capillary water[16] at cell surface. This is of particular benefit for the recovery of extra-cellular product from fermentation broth. Coupling electrodewatering with press filtration has also been attempted, in which a vertical electric field is applied.[5] Compared with the established electrodewatering techniques, the most interesting advantages of the methods presented by the present study are high efficiency in gas discharging and simplicity in construction. These are of essential importance when large-scale separation is considered.

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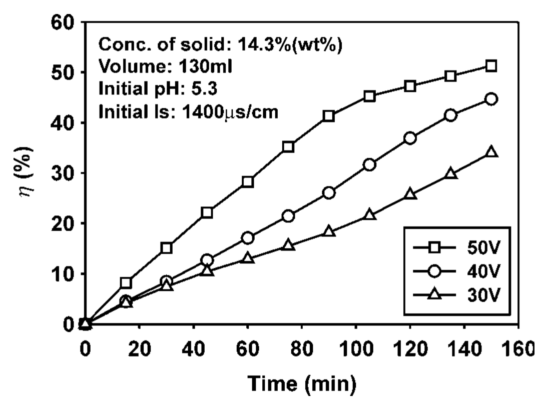

Figure 7. Time course of water removal at different applied voltage.

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CONCLUSIONS

Broth dewatering in a horizontal electric field was investigated using yeast as a model system. The effects of operating parameters on the removal of water from the yeast suspension were examined, which showed that pH, ionic strength, as well as yeast concentration in the suspension have a significant effect on the magnitude of ζ-potential at the surface of yeast, and consequently, the liquid removal efficiency. The maximum dewatering rate can be obtained only under the situation that the average surface charge density over the cross-area of the dewatering cell reaches maximum.

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