Development of a novel high performance filtration system — Application for various hardly filterable materials

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A new filtration method that a slurry is prepared in a well-dispersed state and filtered by a ceramic tube with a spiral guide rod has been developed in our previous paper. In this study, we attempted to concentrate various hardly filterable materials by using this new system. The sample slurries used were sericite, iron oxide, algal suspension, and activated charcoal. Their respective concentrations were 57, 74, 1.1, and 7.55 mass%. The concentrated slurry of all samples exhibited good flowability. In addition, to apply this system to real industrial processes, we attempted to calculate the required number of ceramic filters from the relationship between the filtration flux and the slurry concentration. Thus, the size of this system is expected to be significantly compact. Furthermore, in this system, there is a case that the batch operation is more effective than the continuous operation.

1. Introduction

In dead-end filtration, a cake forms continuously on a filter media and the filtration flux gradually decreases because of the progressive increase in the cake resistance. In order to reduce the resistance, filter cakes are usually added to the feed slurry. Therefore, development of more effective filter cakes has been extensively researched [1–3]. However, because of the addition of filter cakes, the packing fraction of the cake is always relatively low. Moreover, the solids deposited on the filter media cannot flow. Thus, the cake has to be scraped mechanically, which increases the size, complexity, and maintenance cost of the system.

Due to these disadvantages, many researchers are investigating cake-less filtration types such as cross-flow filtration [4–8] and rotating disk filtration [9–14]. In cross-flow filtration, fouling increases energy consumption and cleaning frequency, which in turn increases the production cost. Therefore, many studies have focused on determining operating parameters that minimize fouling or analyzing the mechanism of fouling [15–20]. In rotating disk filtration, fouling-prone slurries can be concentrated; however, it requires high power consumption. On the other hand, several advancements in reducing energy consumption have been reported [6,21,22]. This type of filtration system is relatively more complex than others complicated because of existing the moving parts and mechanical seals associated with its filter rotation in this method.

It was reported that a well-dispersed slurry can retain flowability if it is concentrated [23,24]. Furthermore, we have successfully developed novel gravity filtration [25] and rotating disk filtration [26] systems, in which the dense slurry can be collected continuously without using a scraping device. Unfortunately, the ability to scale-up these systems is limited. Thus, in our previous report [27], a new filtration system using a ceramic tube filter with an internal spiral guide rod was developed. Fig. 1 shows the schematic representation and the internal features of the filtration system. Although similar designs were previously reported [28–31], they were only tested with dilute feed slurries. The following points prove the novelty of the new system: (1) this system has the ability to process a high concentration slurry, (2) the slurry concentration achieved by this system is equal or higher than that of conventional systems, (3) the concentrated slurry has good flowability, and (4) the structure of the system is simple. We previously reported the optimization of operating parameters including the use of the spiral guide rod, pitch of the spiral guide rod, filtration pressure, and circulation flow rate. When sericite slurry was filtrated by this system, it was shown that the filtration flux was dramatically improved (about 30 times) compared with that of the conventional cross-flow filtration system as shown in Fig. 2 [27]. It was also shown that fouled particles could be removed easily, and the filtration flux could be recovered to its initial level by ultrasonication. However, neither the ability of the system to handle various hardly filterable materials nor the scale-up of the system was investigated.

Thus, this study aims to evaluate the new filtration system's ability to process hardly filterable materials and discuss the scale-up of the system. Slurries of sericite, iron oxide, algal suspension, and activated...
sludge of the excrement of farm animals were selected as sample slurries. In current industrial processes, these materials are concentrated by filter press or sun drying. However, there is a demand for more efficient methods. We attempted to use the new system to concentrate these slurries and compared the final concentrations with those of current filtration systems. In addition, we attempted to calculate the number of ceramic filters that was necessary to achieve the target concentration and volume throughput. Moreover, we compared the batch and continuous operation efficiencies of the new system.

2. Concentration test of hardly filterable materials

2.1. Filtration units

The slurry in the feed tank was fed into the filter assembly via a pump and a pressure regulator system as shown in Fig. 1. The filter media was a ceramic tube with a pore size of 1.5 μm. The inner diameter, the outer diameter, and the length were 9, 12, and 300 mm, respectively. The spiral guide rod was fixed concentrically in the ceramic tube. This internal baffle consisted of a 1.5-mm-diameter lead wire wound helically with a pitch of 10 mm around a 6-mm-diameter cylindrical acrylic core. In order to concentrate the slurry up to a target concentration, the slurry was circulated in the system. The filtration pressure and the circulation flow rate were controlled by the pressure regulator and the valve at the outlet of the filter and measured by a pressure gage and flow meter, respectively. The filtration flux was calculated by measuring the filtrate mass at corresponding time intervals. A minimum volume load of 4 L was necessary to maintain circulation. Therefore, this system was limited to a 10-fold increase in concentration because the volume of the feed tank was 40 L.

2.2. Concentration of sericite slurry

The raw material used was sericite powder (average particle size of 4 μm, density of 2.8 g cm\(^{-3}\); Sanshin Mining Co., Ltd., Japan). This sericite powder is used as a cosmetic raw material and its shape is squamous; therefore, it is difficult to filter. Now, in the fabrication plant, the slurry with an initial concentration of 2.8 mass% (1 vol.%) is concentrated up to 55 mass% (30 vol.%) using a filter press. In order to prepare the slurry at a target concentration, sample powder and tap water were weighed beforehand. Afterwards, sample powder was dispersed in tap water. Water-glass (Kanto Kagaku Co., Ltd., Japan) was added as a dispersant at a mass fraction of 0.3 mg g\(^{-1}\) relative to sericite solids. The sericite slurry was prepared at concentrations of 2.8, 24, 41 mass% (1, 10, 20 vol.%, respectively). These slurries were concentrated using the new system, which was operated at a filtration pressure of 0.4 MPa and a circulation flow rate of 16.8 L min\(^{-1}\).

2.3. Concentration of iron oxide slurry

The iron oxide slurry (density of 5.2 g cm\(^{-3}\)) was supplied by JFE Chemical Co. Ltd. The initial concentration was 32 mass% (8.3 vol.%). Now, in the fabrication plant, this slurry is concentrated up to 70 mass% (31 vol.%) using a filter press. This slurry was attempted to concentrate by the new system. This iron oxide slurry, obtained as a residual product from the ironworks, originally contained ammonium sulfate as a flocculant. Therefore, water glass having an additive amount of 2.4 mg g\(^{-1}\) relative to iron oxide solids was added as a dispersant. 40 L of the iron oxide slurry

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Fig. 1. Schematic representation indicating the internal features of the new filtration system.

Fig. 2. Advantage of the new filtration system.
was filtered at a pressure of 0.4 MPa and a circulation flow rate of 16.8 L min\(^{-1}\).

### 2.4. Concentration of algal suspension

An algal suspension sample was collected from a pond in Osaka prefecture in Japan. The initial concentration of the slurry was 0.3 mass\%. This slurry was stable and well dispersed without adding any dispersant. This slurry could not be filtered by a conventional filtration system such as a filter press. Therefore, in the water treatment plant, it was concentrated up to 1.0 mass\% by sun drying.

This slurry was attempted to concentrate by the new system. 20 L of algal suspension was filtered at a pressure of 0.6 MPa and a circulation flow rate of 21 L min\(^{-1}\).

For comparison, the aforementioned algal suspension having initial sample volume of 180 mL was filtered using a dead-end filtration device; the filtration was operated at a pressure of 0.2 MPa.

### 2.5. Concentration of activated sludge from the excrement of farm animals

The initial concentration of the activated sludge derived from the excrement of farm animals was 1.2 mass\%. This slurry was stable and well dispersed without adding any dispersant. This slurry could not be filtered by a conventional filtration system such as a filter press. Therefore, in the excreta treatment plant, the slurry was concentrated up to 7.5 mass\% by sun drying.

This slurry was attempted to concentrate by the new system. 40 L of activated sludge was filtered at a pressure of 0.38 MPa and a circulation flow rate of 17 L min\(^{-1}\).

### 3. Results and discussion

#### 3.1. Concentration of sericite slurry

The relationship between the filtration flux and the volumetric concentration is shown in Fig. 3. The filtration flux decreased gradually with the concentration of the slurry. The slurry was concentrated up to 57 mass\% (32 vol\%), which is comparable with a conventional filter press used in the fabrication plant. At this concentration, although the pump was not able to work well, the concentrate had good flowability, as shown in Fig. 4. In addition, cake was not observed on the spiral guide rod after the experiment.

#### 3.2. Concentration of iron oxide slurry

Fig. 5 shows the experimental filtration results of the iron oxide slurry. The filtration flux also decreased gradually while the slurry was being concentrated. In this test, the slurry was concentrated up to 74 mass\% (35 vol\%). The pump did not work well at 74 mass\%, although the flowability of the concentrate was good, as shown in Fig. 6. On the basis of these results, it appears to be possible to decrease the water content to less than 30 mass\%, which is comparable with a conventional filter press used in the fabrication plant.

#### 3.3. Concentration of algal suspension

Fig. 7 shows the relationship between the filtration flux and the concentration. In this experiment, the filtration test was terminated at 1.1 mass\% because of the shortage of the feed suspension. However,
the filter cake was not observed on the spiral guide rod after end of concentration test and the concentrated slurry had sufficient flowability in order to continue the concentration process.

3.4. Concentration of activated sludge of the excrement of farm animals

Fig. 9 shows the relationship between the filtration flux and the slurry concentration. This slurry was filtered without fouling. The filtration flux initially decreased rapidly because the particles fouled the filter just after starting the filtration process; however, it stabilized similar to that of algal suspension. In this experiment, the filtration test was terminated at 7.55 mass% because of the shortage of the feed slurry. However, the filter cake was not observed on the spiral guide rod after end of concentration test and the concentrated slurry displayed good flowability, as shown in Fig. 10.

4. Scale-up of the system

Scale-up of the filter system is necessary for treating large quantities of samples. In this system, scale-up can be achieved by increasing the number of ceramic filters; the number of ceramic filters can be calculated from the required filtration area. Therefore, we attempted to determine the required filtration area to achieve the target concentration for each of the sample slurries. Furthermore, this was determined for both the batch and continuous operations, and their respective results were compared.

4.1. Batch operation

Assuming a correlation between the filtration flux and the slurry concentration, the required filtration time and filtration area can be calculated as follows.

We considered that the initial \((t = 0)\) slurry, whose volume was \(V_0 \text{ [m}^3\text{]}\) and concentration was \(\phi_0 \text{ [-]}\), is concentrated to \(V \text{ [m}^3\text{]}\) and \(\phi \text{ [-]}\) during \(t \text{ [s]}\). Then, during \(dt \text{ [s]}\), the volume decreased as \(Aq(\phi)dt \text{ [m}^3\text{]}\). Here, \(A \text{ [m}^2\text{]}\) and \(q(\phi) \text{ [m} \cdot \text{s}^{-1}\text{]}\) are the filtration area and the filtration flux, respectively, and the concentration increase is \(d\phi \text{ [-]}\). Assuming there were no particles in the filtrate, this process can be described by the following equation from the material balance equation:

\[
V_0\phi_0 = V\phi = (V - Aq(\phi)dt)(\phi + d\phi).
\]

Now, after the second order incremental term, \(d\phi\), was omitted from this equation, the next equation can be derived:

\[
dt = \frac{V_0\phi_0}{A\phi^2q(\phi)}d\phi.
\]

**Fig. 6.** Photograph demonstrating the flowability of the concentrated iron oxide slurry.

**Fig. 7.** Relationship between the filtration flux and the filtration time of the algal suspension.

**Fig. 8.** Relationship between the filtration flux and the slurry concentration of the algal suspension.

**Fig. 9.** Relationship between the filtration flux and the slurry concentration of the activated sludge.
This equation was integrated \((t: 0 \rightarrow t, \phi: \phi_0 \rightarrow \phi)\) to give the following:

\[
t\phi = V_0\phi_0 \int_{\phi_0}^{\phi} \frac{d\phi}{q(\phi)}. \tag{3}
\]

By using this equation, the relationship between the required filtration time and filtration area can be calculated.

### 4.2. Continuous operation

In the case of the continuous operation, it is necessary to maintain the concentration in the tank at a target concentration of \(\phi_k\) \([-\%]\). At steady state, the slurry, which has a concentration of \(\phi_0\) \([-\%]\), was fed at the flow rate of \(V_f\) \([m^3 \cdot s^{-1}]\) and the concentrated slurry, which has a concentration of \(\phi_k\) \([-\%]\), was discharged at a flow rate of \(V_s\) \([m^3 \cdot s^{-1}]\). The filtrate was drained at a flow rate of \(Aq(\phi)dt\) \([m^3 \cdot s^{-1}]\). From the material balance equation, the following two equations can be obtained:

\[
V_f\phi_0 = V_s\phi_k, \tag{4}
\]

\[
(1-\phi_0)V_f = Aq(\phi_k) + (1-\phi_k)V_s. \tag{5}
\]

By using these two equations, we can calculate the required filtration area for the feed slurry flow rate:

\[
A = \frac{V_f(\phi_k-\phi_0)}{\phi_kq(\phi_k)}. \tag{6}
\]

In the case where the slurry having a total volume of \(V_1\) \([m^3]\) was filtered during \(t\) \([s]\), the volume of \(\alpha\cdot V_1\) \([m^3]\) \((0 < \alpha < 1)\) was filtered by the batch operation, and the remaining volume of \((1-\alpha)\cdot V_1\) \([m^3]\) was filtered by subsequent continuous operation. The relationship between the required filtration time and filtration area of this case is expressed by the following equation:

\[
t\phi = \alpha V_1 \phi_0 \int_{\phi_0}^{\phi} \frac{d\phi}{q(\phi)} + (1-\alpha) V_1 \phi_k \frac{\phi_k-\phi_0}{\phi_k q(\phi_k)}. \tag{7}
\]

### 4.3. Determination of the number of filter tubes of the concentrating system

We considered the concentration of the total volume of \(1\) \(m^3\) of each hardly filterable slurry. We attempted to determine the relationship between the required filtration time and filtration area of the batch and continuous operations by using Eqs. \((3)\) and \((7)\), respectively. In the case of the continuous operation, \(\alpha\) was assumed to be 0.2. However, it was difficult to measure the volumetric concentration of the algal suspension and the activated sludge of the excrement of farm animals, instead the mass concentration was used. \(c\) \([-\%]\) and \(q(\phi)\) \([kg \cdot m^{-2} \cdot s^{-1}]\) were used instead of \(\phi\) \([-\%]\) and \(q(\phi)\) \([m^3 \cdot s^{-1}]\), respectively. In addition, we considered the concentration of the total weight of \(1000\) \(kg\) of each sample slurry. The calculation conditions are summarized in Table 1.

The correlations between the filtration time and the number of ceramic filters for each hardly filterable slurry are shown in Figs. 11-14. In the case where the filtration flux decreased gradually while the slurry was being concentrated, such as sericite and iron oxide slurries, the batch operation was approximately 18 times more effective than the continuous operation. This occurs because, in the case of the continuous operation, it is necessary to always maintain the concentration in the tank at the target concentration, and therefore the filtration flux is always small. However, in the case of the batch operation, it is possible to use all filtration fluxes, including high filtration flux at a low concentration. On the other hand, in the case where the filtration flux initially decreased rapidly just after starting the filtration process, such as algal suspension and activated sludge of the excrement of farm animals, the efficiency of the continuous operation was similar to that of the batch operation.

In the case of the activated sludge of the excrement of farm animals, the maximum number of filters necessary to achieve the target concentration during a one-hour batch operation was 3950.
These filters fit into a box with a length, width, and height of 1000, 1000, and 500 mm, respectively. Compared with the conventional filtration system, such as a filter press, this system is very compact even when the feed tank and the pump are included.

5. Conclusions

In this study, we discussed a cross-flow tubular ceramic filter with an inserted spiral guide rod. We attempted to filter various hardly filterable materials such as sericite, iron oxide, algal suspension, and activated sludge of the excrement of farm animals by the new system. Each sample slurry was concentrated to achieve target concentrations, activated sludge of the excrement of farm animals by the new system.

To apply this system to real industrial processes, we estimated the required number of filter tubes by using the experimental relationship between the filtration flux and the slurry concentration. In each sample slurry, the size of this system can be expected to be significantly compact. Moreover, in this system, the batch operation was estimated to be more effective than the continuous operation.

These results demonstrate the potential applicability of this new system to various industrial processes.

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References


