Development of a novel high performance filtration system — Optimization of operating conditions

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A B S T R A C T
A new filtration system with a spiral guide rod in a ceramic tube and slurry prepared in a well dispersed state has been developed. This paper discusses the optimization of operating conditions such as the effects of the spiral guide rod, the pitch of the spiral guide rod, the filtration pressure and the flow rate of circulation on the filtration flux. In addition, using a filter after filtrating dense slurry, ultrasonication test and repeated filtration tests in short and long intervals were carried out. In this system, it was shown that the filtration flux was dramatically improved compared to the conventional cross-flow filtration system. The filtration flux increased with the flow rate of circulation and did not depend on the filtration pressure. The achieved optimal value of the pitch produced the maximum filtration flux. It was also shown that fouled particles can be removed easily and the filtration flux can be recovered to the initial condition by ultrasonication.

1. Introduction

In many industries, such as the purification of solid materials, the collection of products from solutions after chemical reactions, various types of cake-less filtration, such as flow filtration [1,2], vibration type dynamic filtration [3,4] and rotating disc filtration [5,6], is widely used to concentrate slurry, although there are some problems. In cross-flow filtration, it is difficult to apply to concentrate, and in vibration type dynamic filtration and rotating disc filtration, a large quantity of power is necessary, although it can be applied to concentrate.

However, in our previous reports, alumina slurry with a good dispersion state was evaluated by hydrostatic pressure measurement [7–9], which is a new slurry evaluation method that we proposed. Even if the slurry made a dense layer, it had flowability. In addition, it was confirmed that there is a flowable layer in the upper area of the sediment which is made by gravitational settling [10,11]. Thus, we developed a new filtration system using the addition of dispersants [12]. In this paper, it is shown how dense slurry can be collected without a scraping device by using gravity filtration, however, the filtration flux is not high. Thus, we tried to improve the filtration flux by using a rotating disk [13] and succeeded in the development of a new filtration system in which dense slurry can be collected continuously without any scraping device. In this system, the enlargement of the filter media diameter and an increase in the number of the filter media resulted in an increase in the filtration area.

Unfortunately, it is difficult to enlarge the filter media diameter because there is a moving part in the system. Even if the number of the filter media is increased, it may not always have a good correlation between the increased number of filter media and throughput because an interaction between the filter media occurs. As a result, in this system, there is a limitation in scale-up.

Therefore, we thought that cross-flow filtration could be used again because it can be scaled up easily by increasing the number of filters. However, a high flow velocity is necessary to remove enough particles from the filter surface, therefore, a large pump power is necessary because the ability to sweep away the cake is small in comparison to other cake-less filtration methods. In this situation, generally, backwash is done when the differential pressure increases as a result of cake generation [14]. However, the instrument becomes expensive because it is necessary to make a pressure filter and even if the backwash is done, not all particles can always be removed, and fouling of the particles in the filter often gradually becomes worse and the filtration flux does not recover enough. Therefore, the backwash is not always effective.

The cause of the filtration flux decrease in cross-flow filtration is the concentration of the filter media surface becoming higher. Therefore, we developed a new system which is a kind of cross-flow filtration using a ceramic tube filter inserted into a spiral guide rod for the following reasons, as shown in Fig. 1. First, there is no moving part in this system; therefore the system can be scaled up easily. Second, the shear force acting on the filter inner surface increases and this helps to sweep away the dense slurry from the filter surface easily, which means that the filtration resistance can be reduced and the filtration flux becomes higher. Third, the particle concentration in the
tube becomes homogeneous while the concentration distribution of the radial direction is formed in a conventional cross-flow filtration. Some similar instruments have been developed [15–19]. However, they filtrated diluted slurries because their objective is liquid purification. In contrast, the objective of our research was to treat dense slurry using cross-flow filtration.

In this study, we investigated the effect of the insertion of a spiral guide rod on the filtration flux. In addition, we also investigated the effects of the pitch of the spiral guide rod, filtration pressure and flow rate of circulation on the filtration flux. Furthermore, it was important to investigate the effect of the fouling of particles in the filter on the filtration flux; therefore, using the filter after filtering the dense slurry, ultrasonication and repeated filtration tests in short and long intervals were carried out.

2. Filtration units and slurry preparation

Fig. 2 shows the schematic illustration of the filtration system developed in this work. Slurry in the feed tank is fed into the filter part with a set pressure by the pump. The filter media is a ceramic tube with a pore size of 1.5 μm and the inner diameter, outer diameter and length are 9, 12, and 300 mm, respectively. The spiral guide rod is set in the ceramic tube. The material of the core rod of the spiral guide rod is acrylic. On the core rod, a lead wire is wound as a spiral guide. The diameter of the core rod and the lead wire are 6 and 1.5 mm, respectively. Thus, the gap which is the depth of the channel created by the spiral guide rod is 1.5 mm. In order to keep the slurry concentration constant, both the filtrate and the dense slurry were returned to the tank. The filtration pressure and flow rate of circulation are controlled by the pressure regulator and the valve at the filter outlet is measured by a pressure gauge and flow meter, respectively. The filtration flux was calculated by weighing the filtrate over a period of time.

The slurry preparation method was as follows. The raw material was sericite powder (average particle size of 4 μm, density of 2.8 g cm−3, distributed by Sanshin Mining Co., Ltd., Japan). This sericite powder was used as a cosmetic raw material and its shape was squamous, as shown in Fig. 3. When it was filtered, particles overlapped each other. As a result, high packing fraction cake, which was difficult to go through liquid, was formed. Therefore, this is a difficult material to filter. In order to prepare the slurry at an objective concentration, sample powder and tap water were weighed beforehand. Afterwards, sample powder was dispersed in tap water using a water glass (distributed by Kanto Kagaku Co., Ltd., Japan) as a dispersant. The additive amount of the dispersant was 0.3 mg g−1 sericite.

3. Results and discussions

3.1. Optimization of operating conditions

3.1.1. Experimental procedure

In order to optimize the operating conditions, a filtration test was carried out by changing the insertion of the spiral guide rod, filtration pressure and flow rate and pitch of the spiral guide rod, respectively. Experimental conditions are summarized in Table 1, and each experimental procedure was as follows. In all experiments, the solid concentration was 1 vol%.

To investigate the effect of the spiral guide rod, the prepared slurry was filtrated by this system and the slurry was also filtrated by the ceramic tube without a spiral guide rod (that is, a conventional cross-flow filtration), and the filtration flux was compared to this system.

To investigate the effects of filtration pressure and flow rate, prepared slurries were filtrated by changing the filtration pressure and the flow rate. Filtration fluxes in each filtration condition were compared.

In order to optimize the shape of the spiral guide rod, the effect of the pitch of the spiral guide rod was investigated by changing the pitch of the spiral guide rod. The pitch of the spiral guide rod is the distance of the lead wire whose direction is parallel with the core rod, as shown in Fig. 2. The filtration fluxes with various pitches of the spiral guide were compared each other.
3.1.2. Effect of the spiral guide rod

Fig. 4 shows the time changes of the filtration flux for this system in which the spiral guide rod was inserted into the ceramic tube, and the usual cross-flow filtration system (that is only the ceramic tube without any guide inside it). The filtration flux of this system was almost 30 times larger than that of the usual cross-flow filtration system. Moreover, we could not observe any cake on the filter surface after filtration in this system, while cake was slightly formed in the conventional cross-flow filtration system, as shown in Fig. 5. From these results, we can conclude that the spiral guide rod is very effective in enhancing filtration performance in this system.

Table 1
Experimental conditions for optimization of operating conditions.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Slurry concentration [vol%]</th>
<th>Filtration pressure [MPa]</th>
<th>Flow rate of concentrate [L min⁻¹]</th>
<th>Pitch of the spiral guide rod [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of the spiral guide rod</td>
<td>1</td>
<td>0.4</td>
<td>2.8</td>
<td>6</td>
</tr>
<tr>
<td>Effects of the filtration pressure</td>
<td>1</td>
<td>0.1, 0.4, 0.6, and 0.8</td>
<td>0.75 – 4.3</td>
<td>6</td>
</tr>
<tr>
<td>and flow rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effect of the pitch of the spiral</td>
<td>1</td>
<td>0.1, 0.4, 0.6, and 0.8</td>
<td>0.25–12.1</td>
<td>2–40</td>
</tr>
<tr>
<td>guide rod</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

3.1.3. Effects of filtration pressure and flow rate of circulation

Fig. 6 shows the effects of the flow rate of circulation on the filtration flux in various filtration pressures. From these results, the filtration flux increased with the flow rate of circulation and did not depend on the feed pressure, although in the case of conventional filtration, the filtration pressure controls the filtration flux. A similar result was reported from the experiment of Bendick et al. [20]. This indicates that the shear stress in the filtration unit increases with the flow rate of circulation without changing the filtration pressure and much of the dense particle layer is swept away from the filter surface and the filtration flux becomes much higher. On the other hand, the filtration pressure increases without changing the flow rate of circulation and more particles are pressed onto the filter surface and the filtration resistance increases. Therefore, in this system, an increase in the flow rate of circulation is more effective on the filtration flux than an increase in the filtration pressure.

3.1.4. Effect of the pitch of the spiral guide rod

Fig. 7 shows the effect of the pitch of the spiral guide rod on the filtration flux. There is an optimal value of the pitch that gave the maximum filtration flux. Fig. 8 shows the linear velocity in the ceramic filter. These two figures have a similar tendency. This indicates that the larger the pitch became, the smaller the flow resistance in the filtration unit became, resulting in a higher filtration flux. However, if the pitch was larger than the optimal value, the shear
stress was not enough to eliminate the dense slurry because the filtration flux decreased.

3.2. Effect of fouling of particles in filter media

3.2.1. Experimental procedures

In case this system is used in real industrial fields, it will lead to a reduction in maintenance cost when operating the system without washing the filter. However, if the system is operated without washing the filter, the filtration flux may gradually decrease because fouled particles in the filter gradually increase. Therefore, the effect of repeated filtration experiments in short and long intervals on the filtration flux was checked by the following method. In the short interval test, the sample slurry with a particle concentration of 1 vol% was filtrated until the filtration flux became constant. Afterwards, the fed slurry was replaced with the other one with a particle concentration of 20 vol% and filtrated. In the long interval test, the sample slurry with a particle concentration of 1 vol% was filtrated after the filtration of the other slurry with a particle concentration of 20 vol% or 30 vol% during 4 h. The experimental conditions are summarized in Table 2. The pitch of the spiral guide rod used in these experiments was 10 mm. The filtration pressure and the flow rate of circulation were 0.4 MPa and 6 L min\(^{-1}\), respectively.

In addition, in order to check whether the particles that fouled in the filter could be removed easily or not, the following experiment was carried out. First, a sample slurry with a particle concentration of 30 vol% was filtrated for 4 h. Second, a sample slurry with 1 vol% slurry using a virgin filter and before and after washing its filter by ultrasonication for an hour, and the filtration fluxes of each were compared. The pitch of the spiral guide rod used in these experiments was 10 mm. The filtration pressure and the flow rate of circulation were 0.4 MPa and 18 L min\(^{-1}\), respectively.

3.2.2. Analysis of results

Figs. 9 and 10 show the impact of filtration time on the filtration flux with short intervals and long intervals on the filtration flux, respectively. In the case of short interval filtration, the filtration flux of the dilute slurry decreased once after the dense slurry was filtrated. On the other hand, after filtration of the dense slurry for a long time, the filtration flux gradually increased up to the value obtained from the repeated experiment in the previous section.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Experimental conditions for preventing particle fouling.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiments</td>
<td>Slurry concentration [vol%]</td>
</tr>
<tr>
<td>Short interval</td>
<td>1 to 20</td>
</tr>
<tr>
<td>Long interval 1</td>
<td>1 to 30</td>
</tr>
<tr>
<td>Long interval 2</td>
<td>1 to 20</td>
</tr>
</tbody>
</table>

Fig. 7. Effect of the spiral guide rod pitch on the filtration flux.

Fig. 8. Effect of the spiral guide rod pitch on the linear velocity in the ceramic filter.

Fig. 9. Impact of filtration time on the filtration flux with repeated experiments in short intervals.

Fig. 10. Impact of filtration time on the filtration flux with long-time filtration.
After 1 h of ultrasonic cleaning, the filtration flux recovered to the value obtained when using a virgin filter, even if when the filter was used to filter the dense slurry. Therefore, in cases of filtering sericite slurry, fouled particles that cannot be swept away by shear stress can be easily removed by ultrasonication. These results indicate that, among the particles which moved to the filter surface by filtration, some particles come into the internal filter and are fouled in the pores, and the remaining particles are pressed on the filter media surface, as shown in Fig. 12. The particles fouled in the pores of the filter cannot be removed by shear stress but can be removed by ultrasonication. It seems that the reason why the filtration flux does not completely recover when dilute slurry is filtered after filtering dense slurry for a long time is that there are many fouled particles in the pores of the filter, and filtration resistance increases after the first filtration of the dense slurry. On the other hand, particles pressed on the filter media surface generate a dense particle layer on the filter media surface because the shape of sericite powder is squamous. This dense particle layer has flowability because the sample slurry was prepared in a well dispersed state. Therefore, if the particles are pressed on the filter media surface generate a dense particle layer on the filter media surface because the shape of sericite powder is squamous. This dense particle layer has flowability because the sample slurry was prepared in a well dispersed state. Therefore, if particles foul the filter during filtration, the particles can be removed easily and the filtration flux can be recovered to the initial condition by ultrasonication.

Fig. 12. Schematic illustration of the filter surface during filtration.

4. Conclusions

We developed a type of a cross-flow tubular ceramic filter with a spiral guide rod in which slurry was prepared in a well dispersed state. It was shown that the spiral guide rod dramatically improved the filtration flux compared to the conventional cross-flow filtration system. In this system the filtration flux increased with the flow rate of circulation and did not depend on the filtration pressure. It was also shown that there was an optimal value of the pitch which produced the maximum filtration flux. Therefore, if particles foul the filter during filtration, the particles can be removed easily and the filtration flux can be recovered to the initial condition by ultrasonication.

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References