Relationship between the Discharge Rate and the Maximum Hydrostatic Pressure upon Wet-Grinding of Soybean Using a Double-Disk Attrition Mill

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Wet-grinding of soybean was done in order to investigate the relationship between the discharge rate of soybean slurry from the disk gap and the maximum hydrostatic pressure exerted on the disk gap by a modified double-disk attrition mill. The discharge rate was estimated from the disk rotational speed, disk gap width, and soybean cincentration. The discharge rate, mainly dependent on the disk gap width, decreased with the narrowing of the disk gap width (from 0.254 to 0.115 mm). On the other hand, the maximum hydrostatic pressure exerted was inversely proportional to the disk gap width.

INTRODUCTION

Wet-grinding has been reported as a more effective process for size reduction of coal (Celik, 1988 ; Ito et *al., 1988* ; Koka and Trass, 1985a ; Koka *et al.,* 1985b), dyestuff (Heim and Leszczyniecki, 1985), Si powder (Suzuki and Kuwahara, 1986), and soda-lime-silica mixture (Kanda et *al.,* 1988), The effectiveness of wet-grinding could be increased with the reduction of particle surface energy, depression of particle aggregation, and homogeneous dispersion of particles. In food processing industry in Japan, the wet-grinding processes have been applied to productions of soybean curd, sesame-soybean curd, protein extraction, starch manufacturing, etc. There are, however, few fundamental research works for food materials except the ingredients separation (Fujio and Furuta, 1989 ; Furuta *et al., 1989)* by the wet-grinding process.

In this paper, we demonstrated the relationship between the discharge rate from the disk gap and the maximum hydrostatic pressure exerted on the disk gap.

MATERIALS AND METHODS

Soybean

Dehulled soybean (product of North America, 1989), used in this experiment, was pre-crushed to particle size under 1 mm in diameter with an attrition mill (Jiyu Funsaiki M-2, Nara Kikai Co. Ltd., Tokyo, Japan).

Attrition mill

A commercial single-runner disk attrition mill (NSG-08, Nagasawa Kikai Co. Ltd., Saitama, Japan) was used for the wet-grinding operation. It was mounted on a stationary disk of 80 mesh emery and a runner disk (Noritake Diamond Tools Co.,

Nagoya, Japan) covered with sharp edged diamond particles of 120 mesh. The disk gap width between the stationary and the runner disk was adjustable and measured by a standard thickness gauge. The rotational speed of the runner disk was regulated ranging from 960 to 1,860 rpm. Five pressure taps were mounted within the radial direction of the stationary disk (Fig. 1-2). Hydrostatic pressures exerted by wet-grinding were measured with bourden gauges (Pressure Gauge AS 3/8, Kusaba Gauge MFG. Co. Ltd., Osaka, Japan ; Compound Gauge BU 3/8, Daito Keiki Seisakusho Ltd., Hiroshima, Japan).

Wet-grinding

Pre-crushed soybean was suspended in deionized water, and its concentration was adjusted to 10, **15, 20,** and **25% (w/w).** The soybean slurry was introduced at (a), then passed through the disk gap and discharged from the periphery of disk (b) into the stationary casing of the mill (Fig. 1-l). During the wet-grinding operation, a feed level of soybean slurry was maintained at constant height to keep a certain pressure head and prevent an air inflow. The hydrostatic pressures at five pressure taps (Fig. 1-2), disk rotational speed, and discharge rate from the disk gap were measured during the wet-grinding operation. Maximum hydrostatic pressure was established as the high-est hydrostatic pressure (at Pressure Tap of T_3, T_4, and T,) exerted on the disk gap. Centrifugal force on the soybean slurry was calculated from the logarithmic mean of disk radii of Pressure Tap of $T_3(r_1)$ and $T_5(r_2)$ (Fig. 1-2), discharge rate of soybean
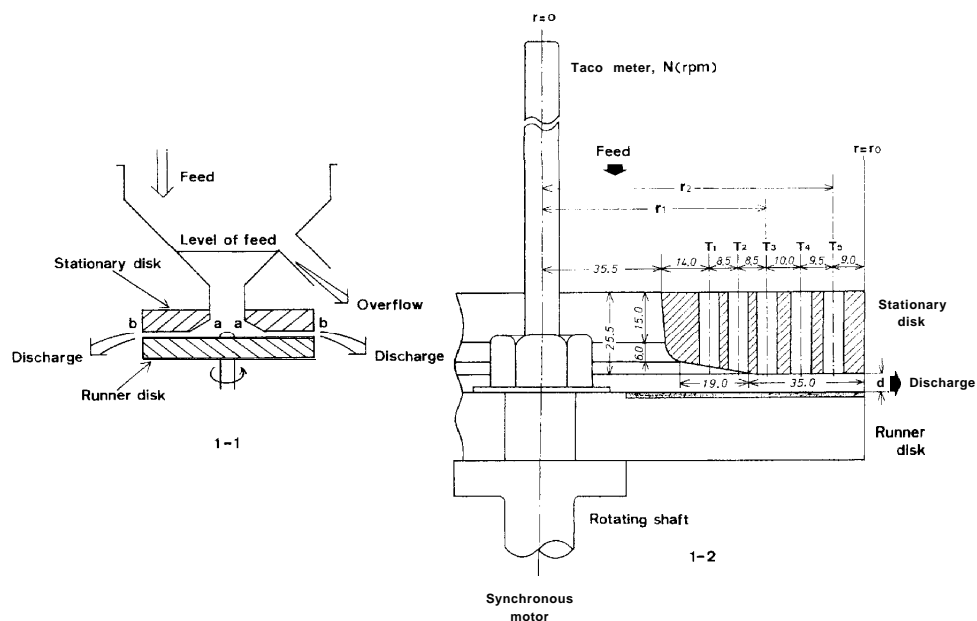

Figure 1. Grinding mechanism of double-disk attrition mill(1-1) and position of pres-sure tap on stationary disk (1-2). a, inlet zone ; b, outlet zone.
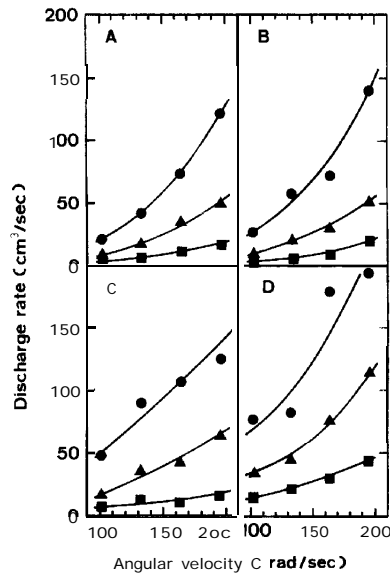
Figure 2. Relationship between disk rotational speed (in angular velocity) and discharge rate of soybean slurry. A, 25% (w/w) soybean concentration ; B, 20% (w/w) soybean concentration ; C, 15% (w/w) soybean concentration ; D, 10% (w/w) soybean concentration. ●, 0.254 mm disk gap width ; ▲, 0.185 mm disk gap width ; ■ , 0.115 mm disk gap width.

slurry, density of soybean slurry, and rotational speed of runner disk.

RESULTS AND DISCUSSION

Effect of disk rotational speed on the discharge rate

Figure 2 shows the relationship between the disk rotational speed (in angular velocity) and the discharge rate of soybean slurry. The discharge rate increased with both the widening of the disk gap width (from 0.115 to 0.254 mm) and the decrease in soybean concentration (from 25 to 10% (w/w)). There were, however, few effects of the soybean concentration (at 15, 20, and 25% (w/w)) at the disk gap widths of 0.115 and 0.185 mm. Hence, for soybean slurry grinding by the double-disk attrition mill, it was proved that the discharge rate of soybean slurry could be determined by the combination of the disk rotational speed, disk gap width, and soybean concentration ; with the discharge rate being mainly dependent on the disk rotational speed.

Centrifugal force occurring in the disk gap

As shown in Fig. 3, the relationship between the centrifugal force (acting on an average discharge volume of soybean slurry per second) and the disk rotational speed (in angular velocity) was replotted on a semilogarithmic scale from the previous data (Fig. 2). The centrifugal force increased when the disk gap widened from 0.115 to 0.254 mm and soybean concentration decreased from 25 to 10% (w/w). Reversely,
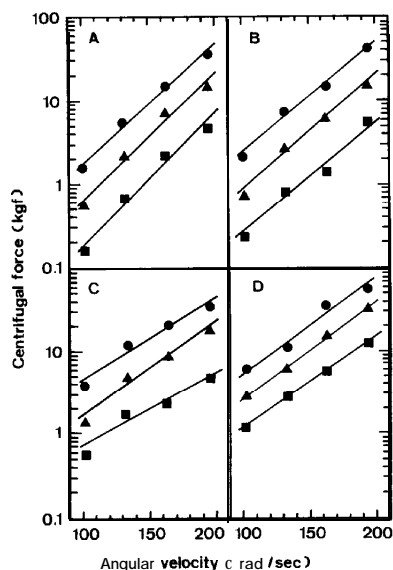
Figure 3. Relationship between centrifugal force acting on average discharge volume of soybean slurry per second and disk rotational speed (in angular velocity). A, 25% (w/w) soybean concentration ; B, 20% (w/w) soybean concentration ; C, 15%(w/w)soybean concentration ; D, 10% (w/w) soybean concentration. ●, 0.254 mm disk gap width ; ▲, 0.185 mm disk gap width ; ■   , 0.115 mm disk gap width.

the centrifugal force acting in the disk gap could be lowered with increasing of the moving resistance of soybean slurry by both the narrowing of the disk gap width and the increase of the soybean concentration.   Considering from the view point of the size reduction of soybean particles, the centrifugal force acting in the disk gap seemed to act as a projectile force of flow, which discharges the soybean slurry out from the disk gap, rather than the attrition force that promoted the size reduction of soybean particles.

Effect of disk gap on the discharge rate
Figure 4 shows the relationship between the centrifugal force (calculated in Fig. 3) and the discharge rate of soybean slurry. A decrease of the centrifugal force resulted to the decrease of the discharge rate, regardless of both the soybean concentration and the disk gap width. However, the discharge rate in the disk gap width of 0.115 mm was extremely smaller than those in the other disk gap widths (of 0.185 and 0.254 mm). Clearly, the discharge rate was markedly dependent on the disk gap width rather than the centrifugal force. The narrowing of the disk gap width thus seemed to function as a rate-limiting step to the discharge rate of soybean slurry.

Relationship between the maximum hydrostatic pressure and the discharge rate
Figure 5 shows the relationship between the maximum hydrostatic pressure (at
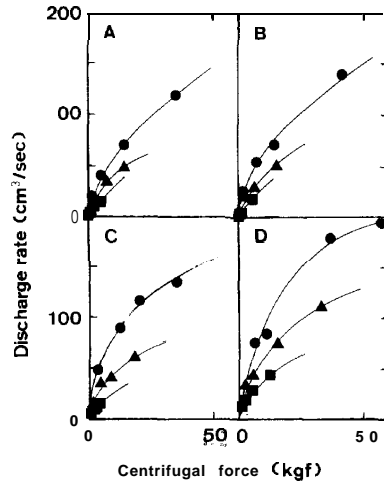
Figure 4. Relationship between centrifugal force acting on average discharge volume of soybean slurry per second and discharge rate of soybean slurry. A, 25% (w/w) soybean concentration ; B, 20%(w/w) soybean concentration ; C, 15% (w/w) soybean concentration ; D,10% (w/w) soybean concentration.   ●, 0.254 mm disk gap width ; ▲, 0.185 mm disk gap width ; ■, 0.115 mm disk gap width.

Figure 5. Relationship between maximum pressure (at Pressure Tap of T,, T_4, and T_5) exerted on disk gap and discharge rate from disk gap.   A, 25% (w/w) soybean concentration ; B, 20%(w/w) soybean concentration ; C, 15% (w/w) soybean concentration ; D, 10%(w/w) soybean concentration.   ●, 0.254 mm disk gap width ; ▲, 0.185 mm disk gap width ; ■, 0.115 mm disk gap width.
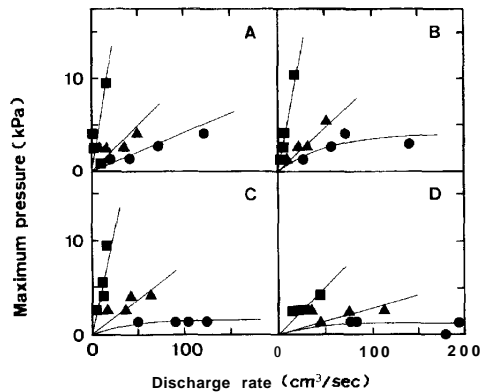
Pressure Tap of T_3, T_4, and T,) exerted on the disk gap and the corresponding discharge rate.   The discharge rate of soybean slurry decreased with the narrowing of the disk gap width (from 0.254 to 0.115 mm), but the maximum hydrostatic pressure exerted on the disk gap conversely increased with the narrowing of the disk gap width. This indicates that the soybean slurry discharged from the disk gap, as shown in Fig.
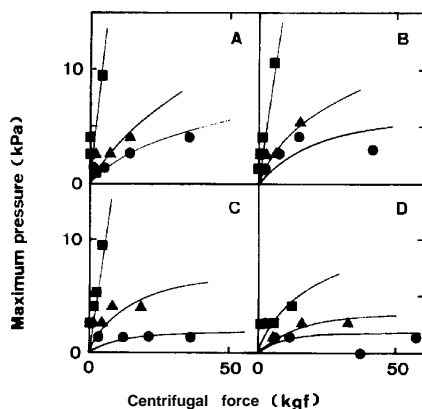
Figure 6. Relationship between maximum pressure (at Pressure Tap of T_3, T_4, and T_5) exerted on disk gap and centrifugal force acting on average discharge volume of soybean slurry per second. A, 25% (w/w) soybean concentration ; B, 20%(w/w)soybean concentration ; C, 15% (w/w) soybean concentration ; D, 10% (w/w) soybean concentration ● ,0.254 mm disk gap width ; ▲, 0.185 mm disk gap width ; ■ , 0.115 mm disk gap width.

3, was guided by a projectile force of flow by disk rotation, but the flow of soybean slurry could be prescribed by the disk gap width. Accordingly, a decrease of the flow of soybean slurry on the basis of the narrowing of the disk gap width (from 0.254 to 0.115 mm) could appear as an increase of the maximum hydrostatic pressure exerted on the disk gap.

Relationship between the maximum hydrostatic pressure and the centrifugal force

Figure 6 shows the relationship between the maximum hydrostatic pressure (at Pressure Tap of T_3, T_4, and T_5) exerted on the disk gap and the calculated centrifugal force. The narrowing of the disk gap width (from 0.254 to 0.115 mm) resulted to a decrease of the centrifugal force, but the maximum hydrostatic pressure exerted, increased with the narrowing of the disk gap width. In the disk gap (of Pressure Tap of T_3, T_4, and T,), a force which was different from the centrifugal force (as a projectile force on the flow of soybean slurry) seemed to act as the attrition force which promoted the size reduction of soybean particles, and such force was enhanced by narrowing the disk gap width. At disk gap widths of 0.254 mm (soybean concentration of 10 and 15% (w/w)) and 0.185 mm (Soybean concentration of 10% (w/w)), the maximum hydrostatic pressures were at relatively constant values in spite of the changes in the centrifugal force owing to changes in both the disk rotational speed and the discharge rate of soybean slurry. The flow of soybean slurry appeared to be more prevalent rather than the size reduction of soybean particles at a disk gap width above 0.185 mm and in a soybean concentration under 15% (w/w).

Consequently, in the case of wet-grinding with a double-disk attrition mill, it could be suggested that Bernoulli's equation applies to the relationship between the discharge rate of soybean slurry from the disk gap and the maximum hydrostatic pressure

exerted on the disk gap. Therefore, we presumed that the size reduction of soybean particles could be affected more by the attrition force acting upon grinding of soybean particles rather than that of the centrifugal force acting to discharge the soybean slurry from the disk gap.

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