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Solid-Liquid Separation of Agricultural Products Using Twin Screw Press and Electro-Osmosis

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Abstract

Solid-liquid separation is one of the main processes in the agricultural and food industry. Screw pressing is one of the methods solid-liquid separation using mechanical pressing. A new type of screw press (twin screw press: screw diameter = 136 mm, L/D = 6.5, feeding rate = 50-150 kg/h) was designed with partial intermeshing and counter-rotation and tested for oil extraction from oilseeds (sunflower, rapeseed), for squeezing juice from cabbage and dewatering of soy milk residue (okara). Oil recovery with a twin screw press increased compared with the use of a single screw press. The oil expressed with a twin screw press contained a smaller amount of foreign material than single screw oil. Other properties of the oil were also satisfactory. Energy consumption of the twin screw press was the most efficient. Juice recovery from cabbage was also highly efficient (88%) with low energy consumption. Since dewatering of fluid material like soy milk residues was difficult to attain a high level of efficiency even using a twin screw press, the application of electro-osmosis was examined and found to be suitable.

Discipline; Postharvest technology/Food
Additional key words: waste treatment

Introduction

Solid-liquid separation process is one of the main processes in the agricultural and food industry, and in the waste treatment of the food industry, this process is also very important. Screw pressing is one of the methods of solid-liquid separation using mechanical pressing. This system which enables to separate liquid from the ingredients continuously with a high capacity, is often used in the agricultural and food industry. Single screw press is used for oil extraction from oilseeds, for squeezing the juice from fruits, etc. Single screw press depends mainly on friction for the material transport which requires a solid core like seed hulls to produce the friction. This process sometimes results in the generation of excessive frictional heat, large energy consumption and product deterioration. Furthermore, single screw press is well recognized for its inadequate ability of crushing and mixing.

The development of a twin screw type may enable to solve these problems due to the improvement in transportation as well as in mixing and crushing functions at the screw interface. In this paper, the effects of the application of the twin screw press will be reported[3,4,7]. For the experiments on dewatering of fluid and wet materials, the application of electro-osmosis will be also reported[5].

Oil extraction 1: Sunflower seed

1) Twin screw design

A partially intermeshing, counter-rotating twin screw press was manufactured by Suehiro EPM (Yokkaichi, Japan). Screw diameter was 136 mm with a length/diameter ratio of 6.5 (Fig. 1). The 2 screws turn in opposite directions. Thus, both high pressure and high shear are generated in the upper intermeshing zone of the screws. Two combinations of

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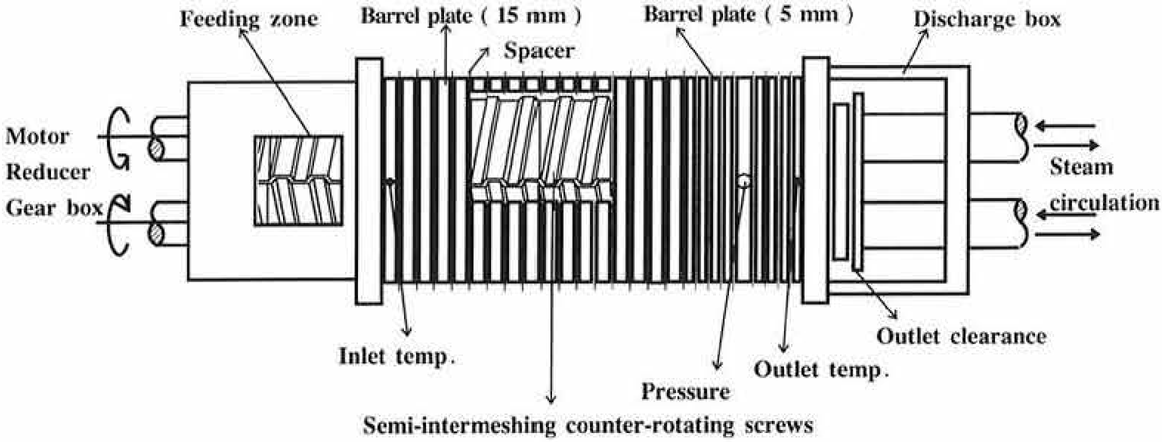

Fig. 1. Schematic representation of twin screw press

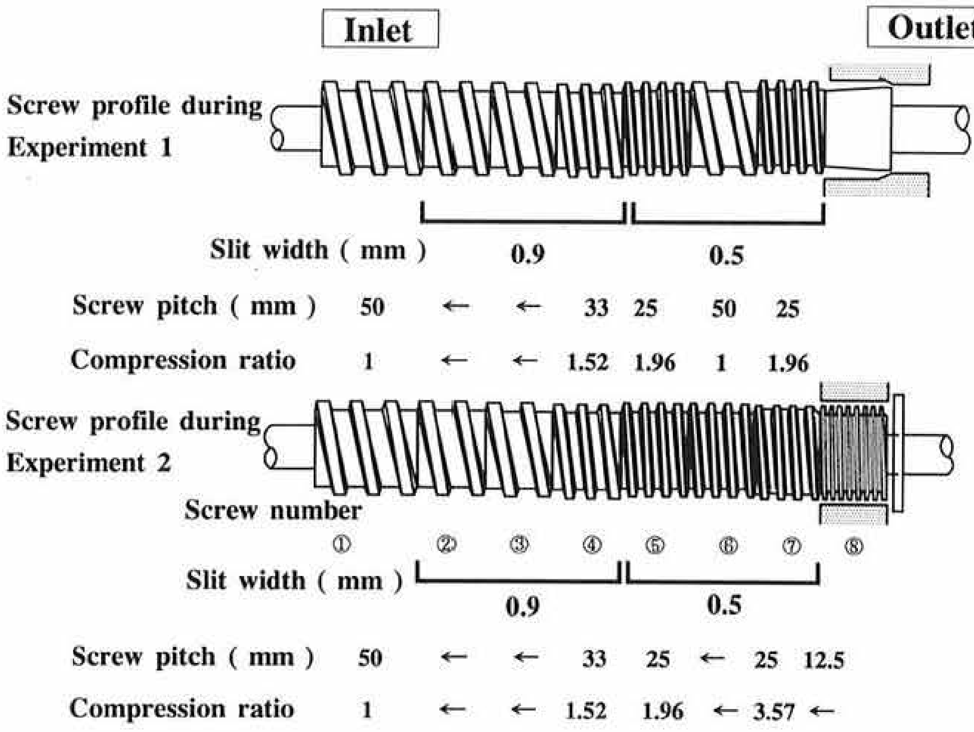

Fig. 2. Screw designs used in Experiments 1 and 2 (sunflower seed)

screw profile, barrel configuration, compression ratio and choke discharge design were used in Experiments 1 and 2, respectively, as shown in Fig. 2.

The barrel consists of 34 vertical parallel plates, separated by spacers, allowing a variable ratio of open to total surface area. Barrel plates with 2 different values for thickness were prepared. The wide type (thickness; 15 mm) has a circulation jacket for cooling or heating. The narrow type (thickness; 5 mm) allows an increased slit filter area. The screw temperature was controlled by the injection of steam in both hollow screw shafts, and the whole screw press temperature was allowed to equilibrate for 2 h before the operation.

A single screw press was also used to compare the results obtained with the twin screws. This expresser is a laboratory scale single screw type manufactured by Suehiro EPM (screw diameter; 56 mm, L/D = 4).

2) Experiment

Dehulled sunflower seeds (*Helianthus annuus* L.) of the variety Hybrid 444 (harvested in Minnesota, U.S.A.) were found to contain 3.20% water, 58.6%

crude oil, 20.3% crude protein, and 1.1% chlorogenic acid. The content of the hulls was lower than 1% by weight in seeds, and bulk and real density values were found to be 0.61 and 1.09 g/cm^3, respectively. Sunflower seeds with hulls were derived from the same variety as above. Hull content was 25%.

The screw press was gravity-fed, maintaining a slight excess of seed above the screw by hand feeding. At a fixed screw speed of 17 rpm the total feeding rate ranged from 50.2 to 58.0 kg/h. Expressed oil was recovered and weighed separately. In some cases, a dead-stop procedure allowed to collect partially defatted presscake at different locations in the screw channel for analysis as described below.

During the expression process, barrel temperature and pressure in the barrel before the outlet discharge were measured. Motor current was also measured to calculate the energy consumption. The only difference between Experiments 1 and 2 was the screw design shown in Fig. 2. Also, in Experiment 1 we decreased the outlet clearance to test the effect on presscake Nitrogen Solubility Index (NSI).

The single screw press was also gravity-fed, and its feeding rate ranged from 19.4 to 22.9 kg/h. The screw rotation was 55 rpm, and the temperature and pressure in the barrel were not measured. Water, oil, foreign material and chemical analyses of crude oil and presscake were performed using standard methods[6]. Particle size distribution of the sample was also measured by the procedure described below. Samples (50 g) of sunflower seeds, final press cake, and intermediate presscake collected on the screw channel, were suspended and shaken at 25°C for 60 min in 200 ml water on a swing shaker at 125 cycles/min. Then the total slurry was successively filtered on 3, 2, 1 and 0.5 mm opening sieves to separate all the particles. All the fractions were dried at 105°C, then weighed for the determination of the particle size distribution of the dry matter. Nitrogen Solubility Index (NSI) of defatted seeds and presscake powders was measured according to the A.O.C.S method[1].

3) Results and discussion

Fig. 3 shows the oil recovery from sunflower seeds with and without hulls. Oil recovery refers to the weight of expressed oil as a percentage of all oil in the starting seeds. The single screw machine could express more than 70% of the oil from seeds with hulls, while almost no oil could be expressed (less than 20%) from dehulled seeds. On the other hand, by using the twin screw press we could obtain a 93.6% oil recovery from dehulled seeds, due to the screw combination. Intermeshing of twin screws has a positive displacement effect, preventing material from rotating with the screw which occurred when the single screw was used for expressing dehulled seeds. Fig. 3 shows additional improvements of dehulled seeds. Oil content of dehulled seeds was 20% higher than that of the seeds with hulls. For similar feeding rates, more oil could be expressed from dehulled seeds. Also, protein content of the presscake was higher when dehulled seeds were used.

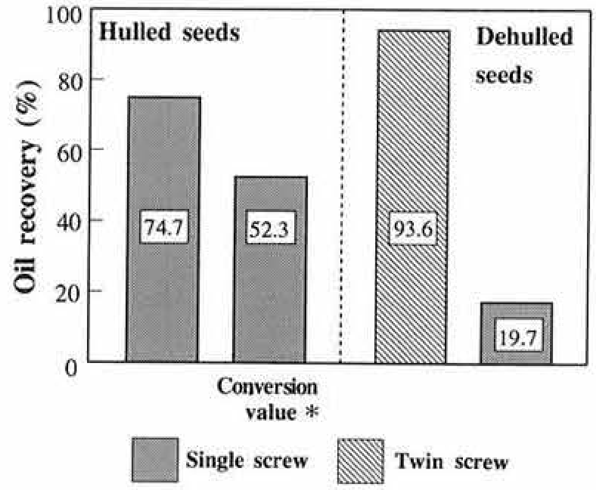

Fig. 3. Oil expression efficiency (sunflower seed)
Oil recovery is calculated as a percentage of total oil in the starting material.
*The converted value was calculated on the basis of dehulled seed weight instead of hulled seed weight.

The quality of oil expressed with the twin screw press was higher than that of oil expressed with the single screw in terms of foreign material content (Table 1). Acid values were similar and lower than in commercial filtered oil. The higher acid value and peroxide value of twin screw-expressed oil suggest that the oxidizing enzyme was not deactivated under the low temperature conditions of twin screw expression and the opportunity for contact increased under these mixing conditions. For reference, commercial type of filtered oil (No. 4) is shown in Table 1. The difference in the α-tocopherol content between 1 - 3 and 4 was caused by differences in the sources of the seed. Table 2 shows the changes in NSI of presscakes using single and twin screw press from the original seed value. NSI value for single screw press decreased more abruptly than when the twin screw was used. This NSI decline may be caused by heat generation associated with shearing

Table 1. Quality of oil expressed from sunflower seeds (Experiment 1)

Screw press	Speed type	Water (%)	α-Tocopherol[a] (mg/100 g oil)	Foreign material (w/w %)	Acid value[a]	Peroxide value[a] (meq/kg oil)	Wax[a] (%)	AOM[a] (h)
Twin screw	Dehulled	0.34	72.0	1.24	1.23	10.8	0.89	7
Single screw	Hulled	0.12	73.2	2.65	1.00	5.3	0.81	7
Single screw	Dehulled	0.91	70.8	8.39	0.97	7.5	0.67	7
Single screw[b]	Hulled	0.07	84.6	0.01	2.03	14.9	0.69	3

a): Analyzed by Japan Research Laboratories. AOM: Active oxygen method for measuring fat stability upon autooxidation; this value is the time (h) required to reach a POV value of 100 under the oxidation condition.
b) Commercial filtered oil from a single screw press (commercial type).

Table 2. Protein change during oil expression (Experiment 1)

	Single screw presscake	Twin screw presscake	
		Wide clearance	Narrow clearance
NSI change ratio[a]	34.3	82.0	60.6

a): This value is the ratio of the NSI value of the presscake to the NSI value of the original seed (%).

in single screw press. By reducing the clearance of the outlet of the twin screw press we increased the amount of shear that went into the presscake. Thus, the proteins were less soluble when a smaller clearance was used.

Dehulled sunflower seeds were used "as is", without any pretreatments, in order to test the screw press efficiency for replacing each step of the conventional pretreatment processes (size reduction, flaking, and thermal treatment). During the expression process, extraction of oil with minimal amount of foreign materials and production of high quality (non-overheated) presscake with minimal remaining oil content and high output were attempted. Energy consumption for oil expression is indicated in Table 3. The twin screw press was confirmed to be the most energy-efficient.

The effect of the improvement of the outlet discharge and addition of narrow pitch screw segments is indicated in Table 4. The amount of foreign materials and energy consumption were reduced and oil recovery slightly increased in spite of the increase of the feeding rate.

Changes in the particle size distribution and oil content of the materials in different areas along the twin screw press are shown in Fig. 4 for Experiment 2. By using the dead stop procedure during the experiment, it was possible to disassemble the screw press barrel while it was still full of the materials, and to sample partially crushed and expressed seeds at different locations. The full expression process can be analyzed therefore as a continuous change of the physical properties and chemical composition of the materials through the screws.

The total barrel length was divided into 2 sections for better recovery of the oil: a feeding and

Table 3. Electrical energy consumption (Experiment 1)

Screw press	Speed type	Expressed oil (kg/h)	Electricity consumption of motor (kWh)	Unit energy consumption (kWh/kg oil)
Twin screw	Dehulled	23.45	3.4	0.14
Single screw	Dehulled	2.86	3.5	1.25
Single screw	Hulled	5.29	3.5	0.67

Table 4. Oil recovery and oil quality expressed from sunflower seed (Experiment 2)

Oil quality				Oil recovery (%)	Expressed oil (kg/h)	Unit energy consumption (kWh/kg oil)
Water (%)	Foreign material (%)	Acid value	Wax (%)			
0.18	0.50	0.93	0.77	93.7	31.9	0.11

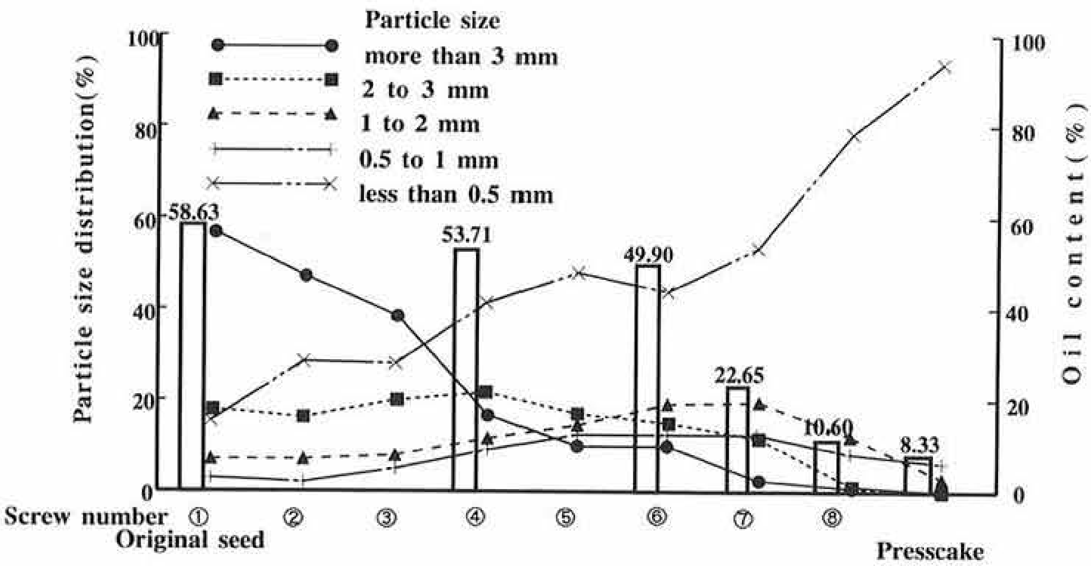

Fig. 4. Particle size distribution and oil content of presscake along the expression path using the dead stop technique - Experiment 2 (sunflower seed)

first step pressing section, with large slit openings, and a high pressure section with narrower slits, to expel more completely oil from the presscake. In the feeding section, sunflower seeds are conveyed by the twin screws, and size reduction begins also as seeds are "flaked" in the intermeshing zone between the 2 screws. The reduction of the displaced volume in the next section allows some oil to be evacuated through large slit openings and not backflow to the feeder. Oil mainly flows from more distant sections where the crushed seeds are actually expressed. It can be noticed that the gradual size reduction is correlated with the design of large slits in the first section (where mainly large seed particles are processed) for maximum drainage of oil almost free from foreign materials. A screw section with a larger pitch is used to separate the first and second sections and to limit the backflow effect. In the high pressure section, the drastic reduction of the available volume, the mixing and crushing effect of the screws and the flow limitation due to the choke, eventually enable to reduce both particle size and oil content of the cake. Final presscake contains mainly agglomerated fine particles and less than 10% oil. The results obtained suggested that this new twin screw press expresses oil from oilseeds with a high efficiency and produces a superior quality oil and meal, especially for the materials that cannot be expressed by single screw presses such as dehulled sunflower seeds. Using a twin screw press may also enable to omit the usual pretreatments of cooking or flaking. As a result, energy consumption for the overall process may become much lower than with the application of single screw processes.

Oil extraction 2: Rapeseed

1) Experiment

A twin screw press was used under the same conditions as those for Experiment 2 for sunflower (Fig. 2). Whole raw rapeseed (Canola: water = 7.94%, oil = 40.70%), cooked rapeseed (water =

Table 5. Operation conditions for oil extraction from rapeseed

Machine type	Rapeseed type	Feed rate (kg/h)	Barrel temperature (°C) Inlet	Barrel temperature (°C) Outlet	Pressure in the barrel (MPa)
Twin screw	Whole dry	90	32.4	73.7	3.8
Twin screw	Whole dry	90	43.9	89.0	0.9
Twin screw	Flaked dry	54	–	–	0.3
Single screw[a)]	Flaked dry	7,500	105.0	93.0	–

a): Commercial process.

3.95%, oil = 42.94%) and flaked rapeseed (water = 8.18%, oil = 39.98%) were expressed using twin screw press, and the crude oil and the presscake were sampled and analyzed as in the case of the sunflower experiment. The same parameters (oil recovery efficiency and oil qualities) from commercial oil expressed were obtained by TOYO Oil Milling Co. in Japan. This commercial process involves pretreatments (flaking and cooking) before expression and uses single screw press (feeding rate = 7,500 kg/h).

2) Results and discussion

Table 5 shows the operating conditions for each process. The temperature of the twin screw press barrel was lower than that of the single screw press, especially with whole raw rapeseed. Even the outlet barrel temperature was about 70°C compared to 93°C for the single screw outlet. These results indicate that since the twin screw press did not generate heat by friction, low temperature processing to obtain good quality oil can be achieved with the twin screw press. Also, the pressure in the barrel was relatively low, resulting in a small amount of foreign materials in the crude oil (Table 6). Table 6 shows the oil recovery and quality. Oil recovery with the twin screw press was not lower than that of the commercial one even in the absence of pretreatment of rapeseed. These results suggest that the twin screw press has a good crushing and mixing ability. Acid value and phosphorus content were lower than in the case of commercial oil, especially for whole rapeseed. Phosphorus contents were one-fourth of the commercial values. It is assumed that the absence of pretreatment and the short time and low temperature processing enabled to avoid the hydrolysis of phosphatides by phospholipase. In the case of low phosphorus oil, oil loss during the degumming and refining processes may be reduced.

Squeezing juice from cabbage

1) Experiment

Twin screw press was tested and evaluated using cabbage to determine its technical performance in order to develop appropriate recommendations for utilization for vegetable juice preparation on a commercial scale.

A twin screw press was used under the same conditions as those for Experiment 2 for sunflower (Fig. 2). Freshly harvested cabbages were cut into small pieces. The twin screw press was fed with a cut cabbage lot previously prepared and pre-weighed. Testing and evaluation involve not only machine operating conditions but also the quality of cabbage juice expressed. Juice quality aspects include color, carbohydrate and protein concentrations and solid content.

2) Results and discussion

The twin screw press enabled to obtain a mean juice recovery of 87.85% (54 kg/h of juice) at a mean feed rate of 67 kg/h. The unit power consumption was 5.73×10^{-3} kWh/kg of juice produced. Mean percentage of solids in juice was 3.65, including a small amount of presscake which can be separated by other means. Only the 'L' color value was affected by the change in the screw speed while the 'a' and 'b' values remained unchanged. Compared

Table 6. Recovery and quality of oil expressed from rapeseed

Rapeseed type	Oil recovery (%)	Oil quality			
		Water (%)	Foreign matter (%)	Acid value	P[a] (ppm)
Whole raw	71.0	0.67	0.72	1.12	37
Whole dry	81.0	0.69	0.95	1.12	116
Flaked dry	70.5	0.70	2.00	2.56	134
Flaked dry[b]	71.1	0.98	–	2.31	475

a): Phosphorus, b): Commercial process.

Table 7. Juice recovery by different processes (cabbage juice expression)

Type of process	Manual expression	Homogenization & centrifugation	Twin screw press
Juice recovery (%)	44.3	30.4	85.6

with the manual methods and a combination of homogenization and centrifugation for juice preparation, the twin screw press led to a high juice recovery (Table 7).

It was concluded that the twin screw press can effectively be utilized for cabbage juice preparation on a commercial scale of operation with only minor modifications in the feed screw and necessary auxiliary feeding device for continuous operation. Suehiro EPM has already manufactured the commercial twin screw press for squeezing juice from carrot.

Dewatering of soy milk residue (okara)

1) Experiment

Tofu is a curd from soy milk which is highly appreciated. The production of tofu also leads to the production of bulky waste known as 'okara'. Okara is the solid residue obtained after the separation of soy milk by squeezing or centrifugation of soybean mash. Milk is added with some coagulant to make tofu. Okara production amounts to about 700 thousand tons annually. Previously, it was used as a food ingredient and animal feed but due to the recent change in food habits and the increase of import of feed materials, its use is now limited. To solve the problem, the development of new dewatering (dehydration) technology for okara is essential. Twin screw press modified for dewatering high fluid material like okara was tested and evaluated. The twin screw press was fitted with a ceramic filter unit (Fig. 5). Fresh okara with adjusted water content (85%) was used in this experiment and the moisture reduction from original to final presscake was determined.

To evaluate the dewatering performance using electro-osmosis, laboratory experiments were carried out using a simple device where the okara sample was subjected to a combination of uniaxial compression and application of electro-osmosis. The device consisted of a 4 cm dia. × 9 cm plastic tube where in the lower part (base) an external thread was provided to receive a cup holding a plastic filter. A stainless wire mesh (400 μm) which acted as the cathode was fitted above this filter and connected to a DC power supply. A sliding fit piston made from titanium and acting as the anode, was used to compress the okara sample placed inside the tube. A set of weights was put on top of the piston to provide a constant pressure to the sample placed between the piston and the filter. In the experiment using low frequency alternative current, a precision power amplifier acting as function synthesizer was used. The initial and final moisture contents of the presscake were determined. Okara was first converted into a slurry with the addition of some water. A 50 g aliquot of slurry was then poured into the tube and allowed to drain for a few minutes to remove the gravitational water. This slurry preparation was made to avoid the entrapment of air in the sample. After drainage, the piston was lowered and a 10 kg-weight (4.4 MPa) and the current were applied. Compression time used ranged from 15, 20 and 30 min.

2) Theory of electro-osmosis

The passage of a liquid through a porous diaphragm with the application of an electric field could be used to dehydrate okara. The principle of this phenomenon is that when particles are dispersed in a liquid, an electric potential difference[2)] is generated across the mobile part of the diffuse charge layer. The value of this potential (referred to as zeta (ζ) potential) depends on the composition of the electrolytic solution as well as on the nature of

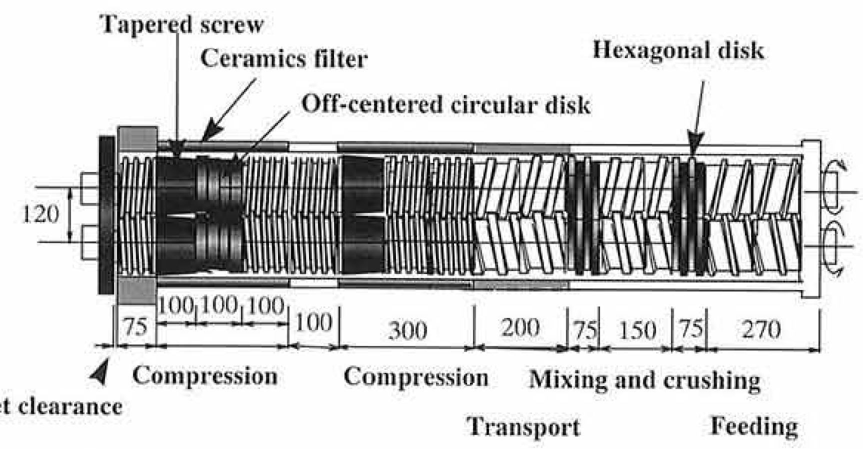

Fig. 5. Schematic representation of twin screw press with ceramic filter

the particle-liquid interface. At the solid-liquid interface, the electrical double layer consists of a layer of ions, with one fixed layer firmly held by the solid and an other more mobile layer equal in magnitude but with an opposite sign to that of the fixed layer. The fixed part of the layer corresponds to the ions adsorbed by the particles to which it owes its charge while the diffuse layer is represented by the charged ions in the solution. By treating the double layer as a simple capacitor, the following relationship was derived:

$$\zeta = \frac{4\pi\eta u}{D}$$

where u is the electrophoretic mobility of the particles (2 to 4×10^{-4} cm/s for most colloidal particles under a potential of 1 V/cm). η and D are the viscosity and dielectric constant, respectively.

The ζ-potential of the particles ranges from 0.03 to 0.06 V when they are dispersed in water. Mobility of the macromolecules is affected by the dielectric constant and the viscosity of the suspending liquid. If the solid cannot move, the fixed layer cannot move too, hence the application of an electrical field will result in the movement of the diffuse mobile part. Direction of the electro-osmotic flow depends on the charge of the diffuse layer. In an aqueous solution, since most solids acquire a negative charge, the diffuse layer has a resultant positive charge. In okara, solids have a negative charge (ca. −2 mV) at pH7. The electro-osmotic flow of water then occurs towards the cathode. Ionic strength of the liquid[8] has a strong effect on the thickness of the double layer and on the ζ-potential. Mobility varies inversely with the square root of the ionic strength as a general rule.

The liquid flow rate from a dewatering sludge bed[10] can be obtained by the determination of the surface area of the bed and the electro-osmotic velocity U_e(cm/s), given by:

$$U_e = \frac{\zeta DE}{\varkappa\pi\eta}(1/300)^2$$

where ζ: ζ-potential of particle, D: dielectric constant of liquid, $\varkappa$: shape factor of particles, η: viscosity of liquid, E: strength of electric field.

Hence the electro-osmotic flow rate Q_e(cm^3/s) is expressed by:

$$Q_e = A\varepsilon_{lw} U_e$$

where A: filtration surface area, ε_{lw}: porosity of water in dewatering sludge bed. Fig. 6 shows the model of electro-osmosis constructed for this study.

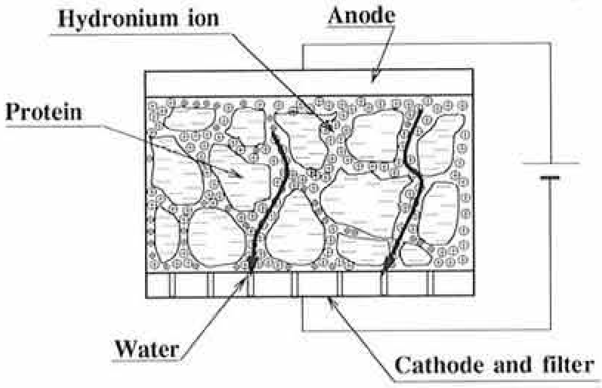

Fig. 6. Model of electro-osmosis for dewatering

3) *Results and discussion*

The amount of water in okara decreased to almost 50% when the twin screw press was used (Table 8). Usually, the single screw press and other continuous mechanical pressure methods could not reduce the water content up to this level. It was found that the twin screw press enabled to reduce the amount of water of okara. However, the presscake still contained 74% water, indicating that if we try to reduce the amount of water more, we have to use another method like the electro-osmosis method. The results of dewatering using the electro-osmosis method are illustrated in Fig. 7 which shows the effects of the electro-osmosis phenomenon. The dewatering rate increased depending on the voltage applied. Heat was also generated under the electro-osmosis treatment. However, these effects did not persist for a long time, because the dewatering process progressed near the upper anode. As a result the sample was partially dried and as the electro-resistance increased, the flowing current decreased. Additionally as the sample pH changed by electro-dialysis, the denatured protein disturbed the liquid flow. Gas was produced and disturbed the flowing current. These shortcomings are a major constraint on the application of the electro-osmosis dewatering method for the food industry. Yoshida reported[9] that electro-osmosis could be applied by using a low frequency

Table 8. Operating conditions for dewatering of okara

Feed rate	76 kg/h
Screw rotation speed	40 rpm
Outlet clearance	0.5 mm
Okara initial water content	85%
Final presscake water content	74%
Efficiency of dewatering	50%

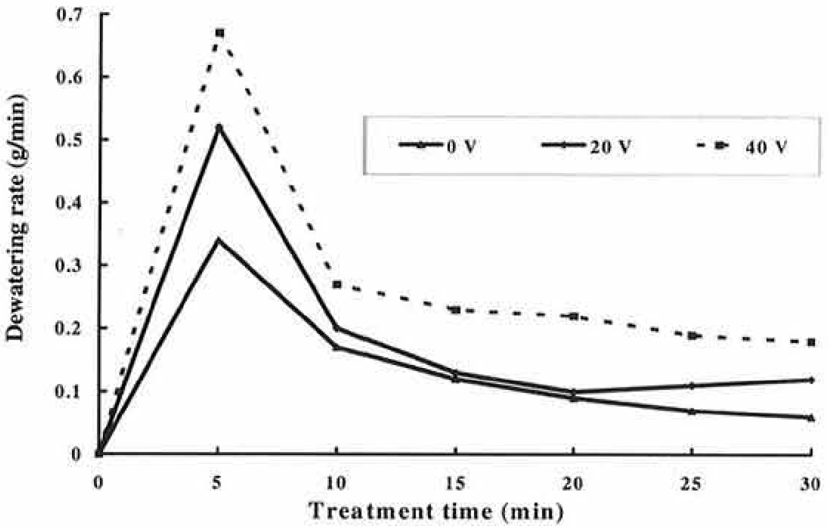

Fig. 7. Dewatering rate from okara by electro-osmosis

alternative current (AC). In this case, clay particles were used as the sample. It was reported that the effect of dewatering at 0.2-0.3 Hz frequency increased compared with normal (DC) electro-osmosis. The author suggested that the AC treatment prevented partial drying during the electro-osmosis. When AC is used for electro-osmosis, pH change near the electrode and gas production may be prevented.

In the experiment using 0.2 Hz and 0.5 Hz, the dewatering rate increased and partial drying was not observed, especially at 0.5 Hz the dewatering rate was twice that of DC treatment and heat generation was also larger. Consequently low frequency AC could be used for the application of the electro-osmosis method to okara dewatering compared with DC treatment. However, in the experiment of AC, gas production and pH change still occurred. These shortcomings and the equipment cost should be alleviated and the combination of this system with a continuous mechanical dewatering system is being considered.

Conclusion

The performance of the twin screw press was examined for oil extraction and juice squeezing. This study shows that the use of the twin screw press for the agricultural and food industry instead of the single screw press could enhance the separation efficiency and improve the quality of the products. One oil milling company plans to scale up the twin screw press for commercial application and one company has already used this twin screw press to produce carrot juice in a commercial line. Unfortunately, high efficiency of dewatering of wet waste like okara was not achieved with the twin screw press. However, dewatering by electro-osmosis suggests that the method could be used for dewatering wet waste. Dewatering and recycling of wet waste from the agricultural and food industry are very important subjects in terms of environmental pollution and limited sources of energy worldwide. The development of a new dewatering technology will be examined based on this study.

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