Mathematical Simulation of an Oilseed Press

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A mathematical model of an oilseed press was developed by superimposition of filtration analysis on screw extrusion theory to calculate press throughput and residual oil content in presscake for a given press geometry and physical properties of oilseed. The model predicted that press performance would improve, i.e., the throughput would increase and residual oil would decrease, if the press were cooled during operation. Longer presses would also give higher throughputs with lower residual oil contents. The predicted effects of changes in shaft speed and choke opening on press performance agreed reasonably well with experimental results obtained on a small laboratory press. A relatively large error of 9.0% in the prediction of throughput could be attributed to changes in viscosity of oilseed mass occurring during its passage through the press. It is expected that use of 'expression' analysis in place of the simple filtration analysis would improve the predictive ability of the model.

Screw presses, or expellers, have been used universally to expel oil from oil-bearing materials for over 80 years. During this period, the presses have been modified extensively to improve their energy efficiency and increase their capacity. However, it would appear from the literature that most of these improvements have come by means of experimentation and intuition rather than on the basis of any rigorous analysis of the physical principles involved in the operation.

During the past two decades, the flow of liquid out of a solid-liquid mixture pressed unidirectionally in a piston-cylinder assembly has been studied extensively on the basis of the consolidation theory of Terzaghi (1). Körmendy (2,3) and Shirato and co-workers (4–6) have developed mathematical analyses for the expression of liquid from clay-water systems to a stage where it is now possible to accurately predict the liquid flow rate for a variety of pressing conditions. Mrema and McNulty (7) also used the consolidation theory to predict the flow of oil from rapeseed and cashew nuts pressed in a piston-cylinder assembly.

Shirato et al. (8) extended their expression analysis for the case of continuous pressing in screw press. Based on that analysis they presented a mathematical model which could calculate the rate of expression of liquid from a solid-liquid mixture (clay-water) passing through a press. This model, however, required the prior knowledge of press throughput, i.e., the axial flow rate of the solid-liquid mixture, and of the pressure profile along the length of the shaft. Because these parameters are unknown for a conceptual press, their model cannot be used for predictive purposes. This paper presents a simple yet more complete screw press model that may be used to predict the performance, namely the throughput and the reduction in liquid content of the solid-liquid mixture, of a press of any given geometry.

MODEL DEVELOPMENT

A simplified sketch of an oilseed press is shown in Figure 1. The shafts in industrial presses have discrete, noncontinuous flights called worm sections. For the sake of simplicity, only continuous flights are considered in the development of the present model (Fig. 2).

The model development was based on the following assumptions:

1. The maceration of oilseed mass was completed in the feed section. Also, the air contained in the

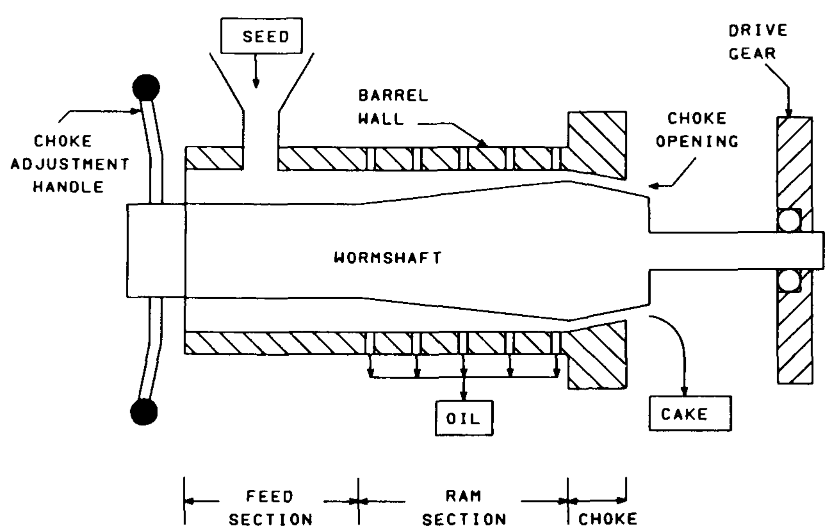

FIG. 1. Simplified sketch of an oilseed press.

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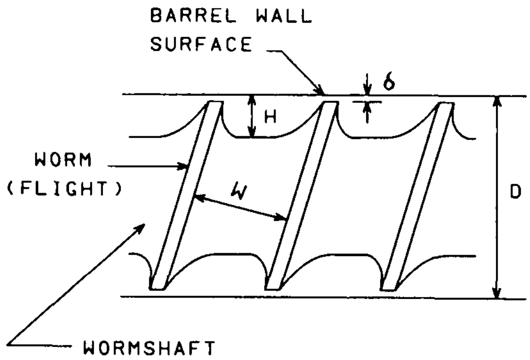

FIG. 2. Continuous helical flight on the wormshaft.

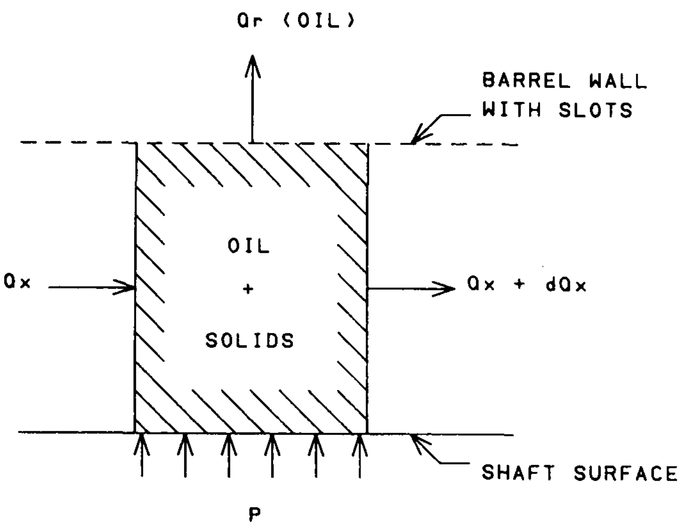

FIG. 3. Flow of material through a section of worm channel.

oilseed was forced out through barrel slots over the feed section, leaving a homogeneous mixture of oil and solids in the ram section.

2. No pressure development would take place in the feed section. The pressure development and hence the expression of oil started at the beginning of the ram section.
3. The temperature of the oilseed mass remained constant in the ram section. In actuality, the temperature would increase along the ram section due to the shearing action of the shaft. However, the press barrel, being a good conductor of heat, would act as a temperature moderator.

Figure 3 shows the material flows through a small section of the worm channel, i.e., the space between the shaft surface and the barrel wall. As the oil-solid mixture passes through the section, it is subjected to radial pressure exerted by the shaft. The pressure causes flow of oil in the radial direction through the solid matrix and out through the barrel slots. This oil flow in turn changes the flow rate of the mixture in the axial direction. A material balance around the section gives:

$$-dQ_x\varrho_c = Q_r\varrho_l \qquad [1]$$

where d is the choke opening, Q the flow rate of oil-solid mixture and ϱ the density. In Equation 1, subscript x refers to direction of worm channel, c to semi-solid mass (oil-solid mixture), r to radial direction and l to oil (liquid phase).

The axial flow of a non-Newtonian fluid in an extruder, a machine similar to an oilseed press except for the absence of slots in the barrel for outward flow of liquid, has been presented by Shirato et al. (9) as:

$$Q_x = \pi DW(H-\delta)N \cos\theta\, f_d/2 - (H^3 W f_{pd} f_{ps}/12\, n\, \mu_c) \bullet dP/dX \qquad [2]$$

where:

$$f_d = 1 - (0.487\, n^2 - 0.948\, n + 0.972)*H/W \qquad [2a]$$

$$f_{ps} = 1 - (0.949\, n^2 - 1.87\, n + 1.59)*H/W \qquad [2b]$$

$$f_{pd} = 0.98 \text{ (for the region of interest)} \qquad [2c]$$

In Equation 2, D is the barrel diameter, W the flight width, H the flight depth, δ the clearance between shaft flight and barrel surface, N the speed of shaft rotation, θ the helix angle, f_d the shape factor for drag flow, f_{pd} the correction factor for average viscosity in pressure flow, f_{ps} the shape factor for pressure flow, n the Power-law index of semi-solid, μ the viscosity, P the pressure exerted by the shaft and X the distance along the worm channel. Equation 2 would be applicable to axial flow in an oilseed press if the solid-oil mixture was treated as a non-Newtonian fluid. The outward flow of oil has been represented by the 'expression' equations for variable pressure condition by Shirato et al. (4,8). Alternatively, the flow can be represented by the basic filtration equation (10):

$$Q_r = \pi\, D\, dX\, u_r \qquad [3a]$$

$$= \pi\, D\, dX\, P/(\alpha_s\, \mu_l\, m_s) \qquad [3b]$$

where u is the velocity of oil flow at the barrel surface, α the specific filtration resistance and m_s the mass of solids in worm channel per unit area of barrel. Subscript s refers to the solid phase. Combination of Equations 1 and 3 with rearrangement gives:

$$dQ_x/dX = [\pi\, D\, P/(\alpha_s\, \mu_l\, m_s)]*(\varrho_l/\varrho_c) \qquad [4]$$

Equations 2 and 4 can be used to evaluate the throughput and the oil expression rate provided the pressure developed in the press is known. The pressure development occurs because of the presence of the end restriction at the choke, and is given by:

$$P = K_c\, K_d\, Q_{die}^n \qquad [5]$$

where K is the consistency index of the semi-solid, K_c a constant, K_d the choke geometric constant, and subscript die pertains to choke, and where Q_{die} is equal to Q_x at the end of the ram section.

The oil content of the mixture at any point along the shaft is calculated as:

$$F = 1 - (1 - F_o)*(Q_o\varrho_{co}/Q_x\varrho_{cx}) \quad [6]$$

where F is the oil content of the oil-solid mixture, and subscript o refers to the beginning of the ram section.

METHOD OF SOLUTION OF MODEL

Because the flow at the end of the shaft had to be equal to the flow through the choke, the model was essentially a boundary-value problem which was solved using a trial and error approach. A numerical method was used in which the ram section of the shaft was assumed to consist of several small sections, each of incremental length ΔX, and the equations were solved preogressively to calculate values of Q, P and F at the end of each section.

For the first trial, a value of Q_o was assumed. For each situation, the initial value of pressure would be:

$$P_o = 0 \quad [7]$$

An initial-value method, the Runge-Kutta 4th Order, was then used to solve, simultaneously, Equations 2 and 4 to obtain the values of P and Q. The oil content at each point was calculated using Equation 6. The viscosity, filtration resistance and density of the oil-solid mixture were evaluated at each point using the P and F values, and were then used for calculation of Q, P and F for the next section.

This procedure was repeated until the end of the ram section was reached. The end P value was used to calculate Q for the choke using Equation 5. This Q was checked against the Q obtained at the end of the ram section. If the error was greater than 2.0%, the initial value of Q was altered accordingly, and the entire calculation procedure repeated until the difference between Q_{die} and Q_{end} was less than 2.0%, where subscript end refers to the end of the ram section.

A computer program was written for the above calculation procedure in Pascal language and was executed on a DOS personal computer. At the beginning of each computer run the input conditions, viz the press temperature, shaft speed, choke opening, etc., were specified. The values of Q_o and F_{end} obtained from the final trial were used to calculate throughput and residual oil content, respectively, as follows:

$$Q' = Q_o*\varrho_{co}*3600 \quad [8a]$$

$$RO = F_{end}*100 \quad [8b]$$

where Q′ is throughput and RO residual oil in presscake. Several computer runs were performed to predict press performance at various input conditions.

METHODS AND MATERIALS

A small oilseed press, the Simon-Rosedowns Mini 40 Screw Press, with a nominal capacity of 40 kg seed/hr was used for pressing experiments. The geometric parameter values of the press were used in the simulation calculations. The barrel of the press was made up of vertical barrel rings which were grooved on the inner surface to facilitate the flow of soft oilseeds such as canola. The spacing between the rings was maintained, as optimized for canola pressing, at 0.51 mm over the feed section. 0.26 mm over the initial half of the ram section, and 0.13 mm near the choke end. Canola (Westar variety) was used as the representative oilseed. The seed had an oil content of 43.2% on the basis of the moisture content at pressing, which was 4.2 ± 0.2%.

Canola pressing experiments. Experiments were conducted at three shaft speeds, 120 rpm, 90 rpm and 70 rpm. Within each press run, the speed was maintained constant and the choke opening was narrowed in stages from 0.80 mm to 0.32 mm. Two kg of cold, i.e. unheated, whole seed was pressed at each opening. The seed was gravity fed from the feed hopper. Before the start of each run, the press was preheated to 45°C by means of a heating pad wrapped around the barrel. One kg of seed was then pressed when the opening was ca. 0.60 mm, to heat up the press to its working temperature range, i.e., to above 80°C. Each experiment was conducted in duplicate.

The pressure just before the choke ring was continuously monitored with a piezoresistive transducer connected to a two-channel recorder. The inside barrel wall temperature was also continuously monitored with a thermocouple connected to the other channel of recorder.

The press throughput was calculated by noting the time required to press the two-kg sample as observed from the pressure chart, which showed a sharp increase in pressure from its zero-level at the beginning of each experiment and a sharp fall to zero-level at the end. The presscake from each experiment was well-mixed and its oil content was determined on a Goldfisch Extractor by AOCS (11) Method No. Ba 3-38.

Estimation of material properties. Semi-solid density. True density of six presscake samples with oil content ranging from 7.5-31.0% was determined using an air comparison pycnometer. The following relation was obtained by regression ($r^2 = 0.96$):

$$\varrho_c = (1.451 - 0.703 * F) * 10^3 \quad [9]$$

Semi-solid viscosity. the viscosity of most food materials can be represented by the power-law model (12). Thus, the viscosity of the semi-solid mass of crushed oilseed inside the press was expressed as:

$$\mu_c = K_c * (\gamma)^{n-1} \quad [10a]$$

$$= K * (\gamma)^{n-1} * \exp(-a*F) * \exp[b/(T + 273)] \quad [10b]$$

where γ is the rate of shear of semisolid mass within worm channel, a the coefficient of oil content term in semisolid viscosity, b the coefficient of temperature term in semisolid viscosity and T the temperature. The choke of the press itself was used as a viscometer for the estimation of parameters in Equation 9. For the annular orifice of the choke, the pressure-flow relationship (13) would be:

$$\Delta P = (2KL/R) * [(2n + 1)/(\pi R^3 n)]^n * (R/d)^{n'} * Q^n * \exp(-a*F) * \exp[b/(T+273)] \quad [11a]$$

where L is the length of choke, R the outer radius of choke (annular orifice) and n′ the power of the (R/d) term in Equation 11a. By taking logarithms of both sides, Equation 10 was converted to following form:

$$\ln(\Delta P) = A + n'* \ln(R/d) + n \ln(Q) - a *F + b/(T+273) \quad [11b]$$

where A is a constant. The pressure drop across the choke was measured for a range of flow rates, and for a range of oil contents of the semisolid mass for temperatures of the mass varying from ca. 95°C to 130°C. Multiple regression analysis of the data was performed to estimate coefficients in Equation 11. A good fit was obtained ($r^2 = 0.95$), and the resultant pressure-flow relation became:

$$\Delta P = 2.39 * 10^6 * (R/d)^{0.269} * Q^{0.1298} * \exp(-18.39*F) * \exp[1476/(T+273)] \quad [11c]$$

Substitution of the respective coefficients in Equation 10b gave:

$$\mu_c = 2.49 * 10^5 * (\gamma)^{-0.8702} * \exp(-18.39 * F) * \exp[1476/(T+273)] \quad [12a]$$

where:

$$\gamma = \pi DN \cos\theta/H \quad [12b]$$

Specific filtration resistance. A compression-permeability (C-P) cell, similar to those described by Grace (14) and Schwartzberg et al. (15), was used for this measurement. Crushed canola mass was placed in a piston-cylinder assembly which was set on a hydraulic press. The mass was subjected to a specific compressive pressure, and oil was passed through it. The oil flowing from the drain at the bottom of the cylinder was collected and flow rate measured. The filtration resistance was calculated by the method of Grace (14). The procedure was repeated at different levels of compressive pressure up to 34 MPa (5,000 psi) and filtration resistance measured at each pressure. The variation of specific filtration resistance with compressive pressure was then evaluated by regression:

$$\alpha_s = 4.3 * 10^9 + 0.8 * 10^3 * P \quad [13]$$

During screw pressing, the oil has to overcome two types of resistance, the resistance offered by individual cell walls through which the oil has to first diffuse out, and the resistance offered by the matrix of solid particles. The specific filtration resistance, as estimated from the C-P cell data, characterized only the second type of resistance. The first type of resistance would be very difficult to quantitate, and hence an empirical correction was made to calculate the combined, or effective (eff), resistance to oil flow:

$$\alpha_{eff} = \alpha_s * f_{per} \quad [14]$$

where f_{per} was called the 'permeability factor' that accounted for the resistance offered by cell walls. This factor was to be determined from actual pressing experiments; it was expected to be greater than one.

Oil density. Density of press oil was determined by weighing 100-ml samples:

$$\varrho_1 = 0.91 * 10^3 \quad [15]$$

Oil viscosity. Viscosity of oil was determined using a co-axial cylinder viscometer ($r^2 = 0.98$):

$$\mu_1 = 4.6 * 10^{-3} * \exp[200.9/(T+50)] \quad [16]$$

Calculation of m_s. The mass of solids per unit filtration area would be given by:

$$m_s = \varrho_s H_c (1 - \varepsilon) \quad [17a]$$

$$= \varrho_s (H+0.003)/(1+e) \quad [17b]$$

where:

$$e = (F/(1-F) * \varrho_s/\varrho_1 \quad [17c]$$

In Equation 17, ε is the porosity (volume fraction of oil in semisolid mass) and e the ratio of volume fractions of oil and solids. The effective height of the solid matrix was taken to be (H + 0.003) to account for the solids in the barrel slots of average depth ca. 3 mm.

Specification of press geometric parameters for simulation calculations. The length of the shaft between feed hopper and choke was 0.158 m. The shaft taper (ram section) started at 0.063 m from the end of the hopper. The corresponding distances along the worm channel (X) were calculated as:

$$X = Z/\sin\theta \quad [18a]$$

where Z is the distance along the shaft axis and θ, the helix angle (taken as average over the entire ram length), was 7.25°. Thus:

$$X_o = 0.5 \quad \text{and} \quad X_{end} = 1.25 \quad [19]$$

The height and width of the worm channel were measured at various points along the channel and were expressed as functions of channel distance:

$$H = 0.0125 - 0.014 * (X-0.5)^{1.1} \quad [20a]$$

$$W = 0.0215 - 0.005 * X^{3.36}$$

Other dimensions of the press were:

$$D = 0.06; \quad \delta = 0.001; \quad L = 0.03; \quad R = 0.029 \qquad [21]$$

The choke opening and the shaft speed were varied for the simulation runs as d: 0.25 to 0.85 mm; N: 70 to 120 rpm.

RESULTS AND DISCUSSION

Permeability factor. The factor was estimated by trial and error so that the residual oil content in presscake, as predicted by the model, was equal to that obtained experimentally at one set of conditions (arbitrarily chosen as N = 120 rpm, d = 0.61 mm). The value obtained for the factor by this method was:

$$f_{per} = 100.0 \qquad [22]$$

Mrema and McNulty (16) reported that the pores in cell walls were very small when compared to cell wall area. Thus, the resistance to oil flow at the cell wall was expected to be far greater than that encountered during flow between walls and between crushed seed particles. Hence the value of 100.0 was considered to be reasonable. This value was used in the model for the other simulation conditions.

Effect of temperature on press performance. Several simulation runs were conducted by varying the press temperature in the range 80°C to 150°C. The extraction efficiency, an index inversely related to the residual oil in presscake, improved steadily as the temperature was lowered (Fig. 4). The press throughput also increased at lower temperatures. Both these positive results would indicate that press performance could be improved if the press was cooled during operation. The benefits from the improved performance, however, would have to be balanced against the cost of press cooling. In the oilseed crushing industry, the full-press machines are cooled to ca. 120°C, the main objective being to prevent discoloration of oil (17,18). Anderson (19) reported that when the SuperDuo Expeller manufactured by the V.D. Anderson Co. was cooled to improve the color of oil, some improvement in the extraction efficiency was achieved, i.e., the residual oil content of soybean presscake was reduced by nearly 0.5 percentage points from the previous levels of ca. 4.0%. In later papers, Ward (17) and Bredeson (18) referred to the potential of extraction improvement by press cooling.

Effect of shaft length on press performance. Length of the ram section was varied, and the height and width of flight at the beginning and at the end of the section were kept constant. The press throughput increased and residual oil decreased on increasing the length of shaft (Fig. 5). Thus presses with longer shafts, and hence with longer barrels, should give better extraction performance. Ward (20) has reported that presses with longer barrels gave higher throughputs.

Similar runs with changes in other geometric parameters of the press, such as barrel diameter, choke length, height and width of flights, etc., would show the effects of individual parameters on press performance. This would not only provide useful insight into the mechanics of screw pressing but also give guidance in the improvement of press design.

Effect of choke opening and shaft speed on residual oil. The actual values of press temperature as measured during the pressing experiments were used for these simulations. The simulated results showed a decrease in residual oil at narrower choke openings (Fig. 6). This effect was obviously a result of higher end pressure due to the increased flow resistance at narrower openings of choke. The simulated curve closely matched the experimental results.

The model correctly predicted that residual oil would be lowered at slower speeds of shaft rotation (Fig. 7). The reduction in residual oil would be a result of longer

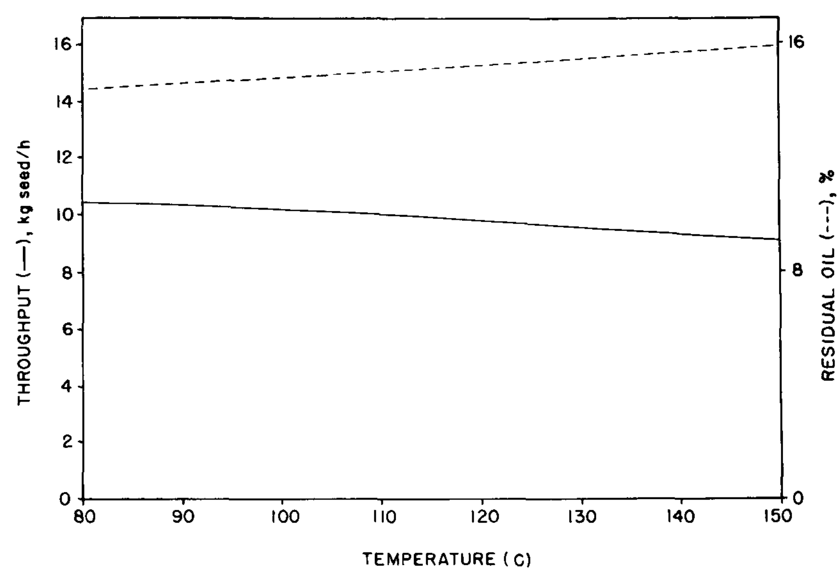

FIG. 4. Simulation of the effect of temperature of the press on throughput and residual oil in presscake at shaft speed 120 rpm and choke opening 0.61 mm.

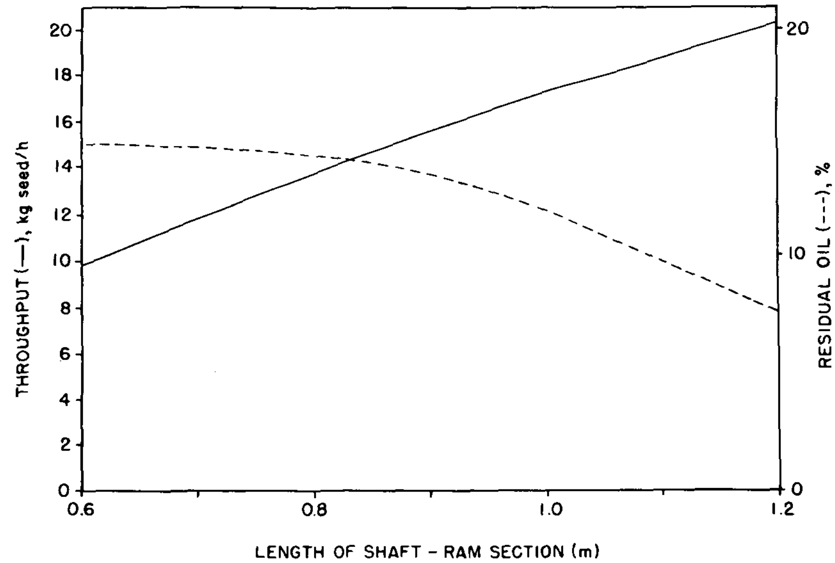

FIG. 5. Simulation of the effect of shaft length on throughput and residual oil in presscake at shaft speed 120 rpm, choke opening 0.80 mm and press temperature 100°C.

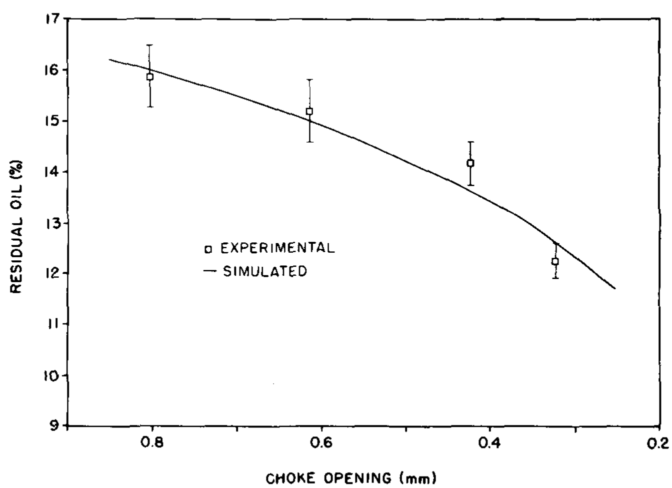

FIG. 6. Simulated and experimental data for the effect of choke opening on residual oil in presscake at 120 rpm.

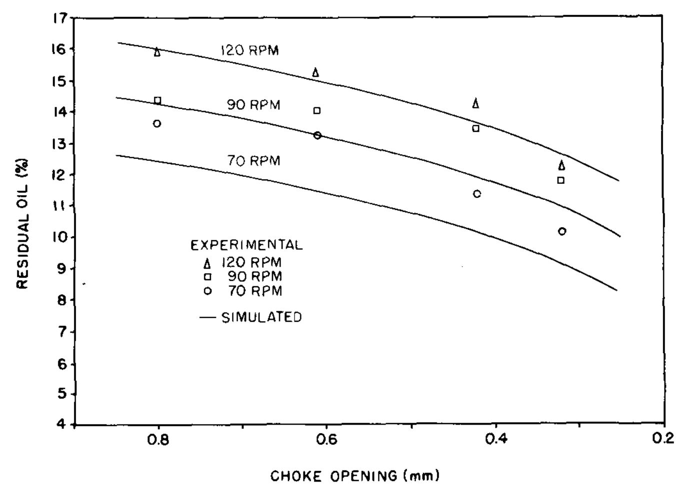

FIG. 7. Simulated and experimental data for the effect of shaft speed and choke opening on residual oil in presscake. Average standard deviations were 0.86, 0.69, 0.46 and 0.49 units at the choke openings of 0.80 mm, 0.61 mm, 0.42 mm and 0.32 mm, respectively.

residence time caused by slower conveying action at the lower speeds. An additional reason may be a corresponding increase in the end pressure due to increased semisolid viscosity at lower speeds (21). The average error of prediction, i.e., the arithmetic mean of absolute values of the individual point errors which were calculated as:

$$\text{Percent error} = [(\text{Predicted value} - \text{Mean experimental value})/(\text{Mean experimental value})] * 100 \quad [23]$$

was ±6.4% for the 12 experimental points in Figure 7.

Effect of choke opening and shaft speed on press throughput. The model predicted that press throughput would decrease when either the opening was narrowed or when the shaft speed was lowered (Fig. 8). The trends matched the observed experimental values. The average error of prediction was ±9.0%. This level of error would be quite reasonable in view of the nonhomogeneous and reactive nature of the material being processed.

A major limitation of the simulation model was that it failed to predict the changes in throughput with changes in choke opening to any significant degree (Fig. 8). This limitation could be explained on the basis of changes in material characteristics, during the passage through the press, unaccounted for in the model.

It is well known that, in a screw extruder, the flow-

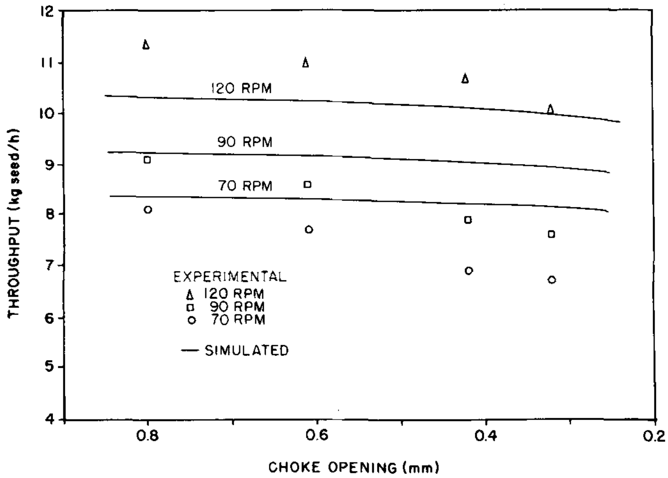

FIG. 8. Simulated and experimental data for the effect of shaft speed and choke opening on press throughput. Average standard deviations were 0.96, 0.80, 0.57 and 0.61 units at the choke openings of 0.80 mm, 0.61 mm, 0.42 mm and 0.32 mm, respectively.

ing mass is subjected to intense churning and shearing action (22, 12). An oilseed press has an internal construction similar to that of an extruder, and the oilseed mass would be subjected to similar churning action. It is possible that the churning action could break some linkages among chains of proteins and carbohydrates which could result in a reduction of viscosity of oilseed mass. Any reduction in viscosity would cause a decrease in press throughput as indicated by Equation 2. A higher end pressure should cause more intense churning, and the reduction in viscosity and in throughput would be more pronounced. At narrower choke openings the pressure would be higher and the reduction in press throughput due to viscosity change would be more pronounced.

It was not possible to account for the reduction in viscosity in the theoretical model, because the extent of linkage breaking and its effect on viscosity cannot be quantified at the present time. If a 10% reduction in viscosity were assumed at the opening of 0.42 mm, as compared to the widest opening of 0.80 mm at 90 rpm shaft speed, the simulated throughput would be 8.26 kg seed/hr instead of the original prediction of 8.96 kg seed/hr. This would reduce the error of prediction at that point from 13.1% to 4.3%. Thus most of the deviation in Figure 8 could be explained on the basis of viscosity changes occurring within the press.

Application of the model. The value for the permeability factor estimated at 100.0 showed that the resistance to oil flow by diffusion through the cell wall is much greater than that offered by the matrix of oilseed particles. The simulation results at different press temperatures indicated that press performance would improve if the press were cooled during operation. The results from the simulation runs at various shaft lengths demonstrated that such a model would be a useful tool for prediction of performance of presses of different geometric configurations and hence would help in the design of presses. The model correctly predicted that the residual oil in presscake and press throughput would both decrease at narrower choke openings and at lower shaft speeds. The residual oil content was well predicted with an average error of ±6.4%. The error in the prediction of press throughput was ±9.0%. Much of the deviation in throughput prediction could be explained on the basis of changes in material viscosity occurring within the press.

On the basis of the above results which showed that the simulation model could predict most of the trends of change in residual oil content and press throughput at various simulation conditions, it may be concluded that the approach taken to develop the model, i.e., superimposition of filtration analysis on the screw extrusion theory, was valid. Further improvements in the model, specifically the prediction of changes in permeability factor and in semi-solid viscosity along the length of the shaft and incorporation of 'expression' analysis instead of the simple filtration analysis, could be expected to improve the predictive ability of the model.

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REFERENCES

1. Terzaghi, K., in *Theoretical Soil Mechanics,* John Wiley and Sons, New York, 1943, pp. 265–296.
2. Körmendy, I., *J. Food Sci. 29*:631 (1964).
3. Körmendy, I., *Acta Aliment. 3*:93 (1974).
4. Shirato, M., T. Murase, M. Negawa and T. Senda, *J. Chem. Eng. Japan 3*:105 (1970).
5. Shirato, M., T. Murase, M. Negawa and H. Moridera, *Ibid. 4*:263 (1971).
6. Shirato, M., T. Murase, K. Atsumi, T. Aragaki and T. Naguchi, *Ibid. 12*:51 (1979).
7. Mrema, G.C., and P.B. McNulty, *J. Agric. Eng. Res. 31*:361 (1985).
8. Shirato, M., T. Murase, N. Hayashi, K. Miki, T. Fukushima, T. Suzuki, N. Sakakibara and T. Tazima, *Int. Chem. Eng. 18*:680 (1978).
9. Shirato, M., T. Murase, and M. Iwata, *Ibid. 23*:323 (1983).
10. McCabe, W.L., and J.C. Smith, in *Unit Operations of Chemical Engineering,* McGraw-Hill Kogakusha, New Delhi, India, 1976, pp. 932-948.
11. *Official Methods and Recommended Practices of the American Oil Chemists' Society,* edited by W.E. Link, AOCS, Champaign, IL, 1973, Method Ba 3-38.
12. Harper, J.M., in *Extrusion of Foods-Vol. I,* CRC Press, Boca Raton, FL, 1981, pp. 47-91.
13. Frederickson, A.G., and R.B. Bird, *Ind. Eng. Chem. 50L*:347 (1958).
14. Grace, H.P., *Chem. Eng. Prog. 49*:303 (1953).
15. Schwartzberg, H.G., J.R. Rosenau and G. Richardson, *Am. Inst. Chem. Eng. Symp. Ser. 73 (167)*:177 (1977).
16. Mrema, G.C., and P.B. McNulty, *Irish J. Food Sci. Technol. 8*:59 (1984).
17. Ward, J.A., *J. Am. Oil Chem. Soc. 53*:261 (1976).
18. Bredeson, D.K., *Ibid. 55*:762 (1978).
19. Anderson, R.T., *Oil and Soap 14*:149 (1937).
20. Ward, J.A., *J. Am. Oil Chem. Soc. 61*:1358 (1984).
21. Vadke, V.S., and F.W. Sosulski, *Ibid. 65*:1169 (1988).
22. Bruin, S., D.J. van Zuilichem and W. Stolp, *J. Food Proc. Eng. 2*:1 (1978).

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