Modeling Solvent Extraction of Vegetable Oil in a Packed Bed

G.C. Majumdar[a,*], **A.N. Samanta**[b] **and S.P. Sengupta**[b]
[a]Department of Agricultural and Food Engineering and [b]Department of Chemical Engineering,
Indian Institute of Technology, Kharagpur, 721 302 India

ABSTRACT: A one-dimensional model was developed for solvent extraction of oil from a packed bed of oil-bearing vegetable materials. The equilibrium relationship between the residual oil content of marc and oil concentration of stagnant miscella in pores of the bed material was generated through experiments with rice bran and hexane. The nondimensional parameters recognized from the model describing extraction were initial Reynolds number (Re_i), initial Schmidt number (Sc_i), bed void fraction (ε_b), particle porosity (ε_p), ratio of bed diameter to particle diameter (D_t/d_p), ratio of bed depth to bed diameter (L/D_t), ratio of particle surface area to bed cross-section ($a_pAL/A = a_pL$), and recycle of solvent and equilibrium distribution coefficient (EDC). For reducing the time required to extract to the same residual oil content of marc, higher values of Re_i, ε_b, and a_pL were beneficial, whereas higher values of Sc_i, ε_p, D_t/d_p, L/D_t, and EDC were detrimental.

JAOCS 72, 971–979 (1995).

KEY WORDS: Equilibrium, modeling, packed bed, residual oil, rice bran, solvent extraction.

A review of the literature suggests that, while considerable experimental work in solvent extraction of vegetable oil has been carried out by various researchers, efforts to model the process have been inadequate. For modeling extraction, the efforts of Fan and Morris (1), Lee *et al.* (2), Karnofsky (3), Abraham *et al.* (4), and Chien *et al.* (5) should be recognized. However, all previous work either failed to appreciate the transient nature of the process of solvent extraction in a packed bed or could not identify the variables that govern the process and, as a result, failed to determine the effects of the variables.

In the present work, an attempt was made to develop a one-dimensional transient model for the process of extraction in a packed bed. A nondimensional scheme was adopted to identify and study the effects of variables that govern the process of extraction.

Theoretical model. The packed bed was conceived to be pretreated (mechanically crushed, expressed, or pelletized) oil-bearing vegetable materials or seeds in a vertical column into which solvent entered from the top. The solvent percolated down through the interparticle void space and picked up oil from the solids on its way. The solvent and oil solution, termed miscella, exited the bottom of the bed.

Figure 1 shows a packed-bed column with an enlarged view of particles of an oil-bearing vegetable material. Pretreating the solids developed macro pores upon complete breakdown or rupture of cell walls. Part of the solvent entered these pores and dissolved the oil instantly. The miscella residing in these pores was considered a stagnant phase. The remaining part of the solvent flowed down through the interparticle void space as the continuous or bulk phase.

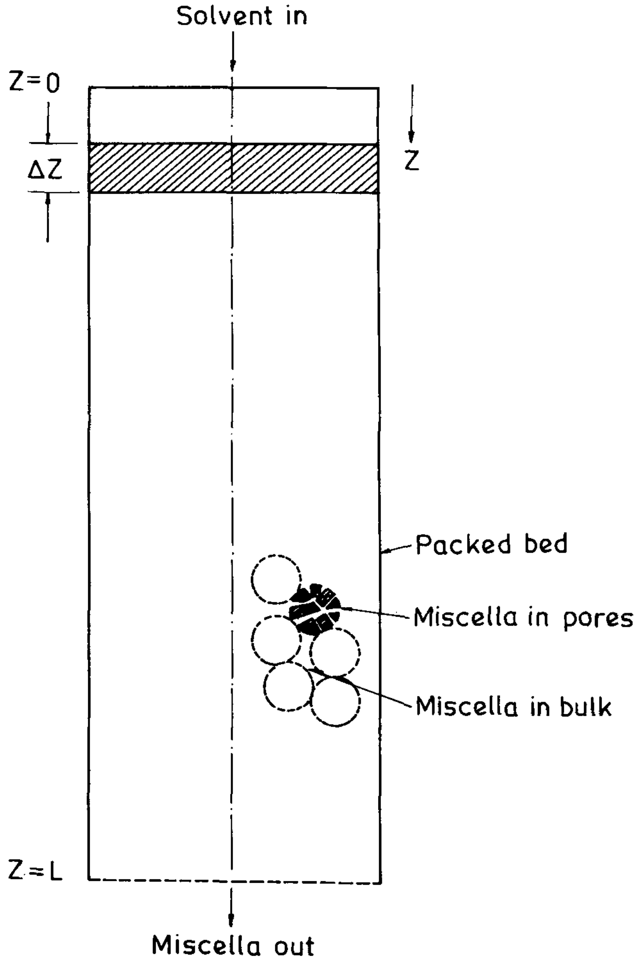

FIG. 1. Section of packed column with enlarged view of particles; Z, axial direction of depth (m); ΔZ, slice width in bed (m); L, depth of bed (m).

---

*To whom correspondence should be addressed.

Abraham *et al.* (4) recognized the equilibrium relationship between the residual oil content in the marc (solvent-laden solids) and the oil concentration in stagnant miscella in the pores. They also suggested that different oil concentrations in the miscella caused changes in the binding force of the surface of the solid. Thus, the oil concentration in stagnant miscella in pores at any point of time was considered to be in equilibrium with the residual oil content of the solids. A change in the oil concentration in stagnant miscella in pores brought about a change in the residual oil content of the solids, which was governed by the system-specific equilibrium relationship that could only be obtained through experiments.

The miscella in the bulk phase that flowed down the bed through the interparticle void space had a leaner oil concentration compared with the oil concentration in the stagnant miscella in pores. At any section of the bed and at any point in time, there was always a difference between the oil concentrations of the pore and bulk miscellas. This resulted in transfer of oil (solute) from pore to bulk phase. As a consequence, for that section and at that time, the oil concentration of the pore miscella changed. This brought about fresh dissolution from residual oil in solids in accordance with the equilibrium relation between the oil concentration of the stagnant miscella in pores and the residual oil content of the marc.

As the bulk miscella flowed down the bed, picking up oil from the pores, an oil concentration gradient developed in the bulk phase along the depth of the bed. This resulted in a minimum concentration gradient at the top of the bed (entry of solvent) and a maximum concentration gradient at the bottom of the bed (exit of miscella). The concentration gradient induces diffusive mass transfer of solute in the direction from higher to lower solute concentration zones. Therefore, in the bulk miscella, diffusion mass transfer of oil took place from the bottom toward the top of the bed, which was in the direction opposite to the flow of bulk miscella. This phenomenon will hereafter be referred to as dispersion.

Assumptions. The assumptions made in developing the proposed model were: (i) Vegetable oil was regarded as a single component because all glycerides are highly soluble in hexane. Further, for crushed oil-bearing vegetable materials, phosphatides could not block the access of hexane to the oil in solids. It was assumed, in line with Karnofsky (6,7), that cell walls were completely ruptured. (ii) The solids had macro-size pores in which oil globules resided; solvent entered these pores and instantly dissolved the oil, resulting in the formation of miscella (stagnant phase). An equilibrium relationship became established between the oil concentration of the stagnant miscella in the pores and residual oil content of the marc. (iii) At any section of the bed and at any point in time, transfer of oil occurred from the pores to the bulk, due to the oil concentration difference between miscellas in the two phases. (iv) In the bulk phase, viewed in isolation, a concentration gradient occurred in the direction opposite to the flow of bulk miscella, resulting in dispersion of oil. (v) Bed depth to bed diameter ratio (L/D_t) was large to allow for no radial oil concentration gradient. (vi) Constant and uniform void fraction in the bed. (vii) Symmetry along the θ-axis. (viii) Constant and uniform particle porosity. (ix) Constant and uniform temperature. (x) No heat of mixing. (xi) The equilibrium relationship generated through experiments accounted for the effect of moisture in the solids.

Mathematical formulation. Mass balances for the miscella and for the solute (oil) were determined for the volume element A • ΔZ of the packed bed.

Overall continuity in the bulk phase. The various contributions were:

Time rate of mass input of miscella across the face at Z due to convective flow

$$= [A \bullet \varepsilon_b \bullet V_s \bullet \rho_l]\big|_Z$$

Time rate of mass output of miscella across the face at Z + ΔZ due to convective flow

$$= [A \bullet \varepsilon_b \bullet V_s \bullet \rho_l]\big|_{Z+\Delta Z}$$

Time rate of mass contribution to bulk miscella in the volume element due to mass transfer of solute (oil) from the stagnant phase in pores to the bulk phase

$$= [k_f \bullet A \bullet \Delta Z \bullet (1-\varepsilon_b) \bullet a_p \bullet \rho_l \bullet (C_p - C)]$$

Writing the mass balance for the volume element and taking limits as ΔZ → 0:

$$\begin{bmatrix}\text{time rate of mass of}\\ \text{bulk miscella input}\\ \text{input across the face Z}\end{bmatrix} + \begin{bmatrix}\text{time rate of mass of oil}\\ \text{contributed to bulk from}\\ \text{pore due to diffusion}\end{bmatrix} = \begin{bmatrix}\text{time rate of mass of}\\ \text{bulk miscella output}\\ \text{across the face Z} + \Delta Z\end{bmatrix}$$

led to

$$\frac{dV_s}{dZ} = \frac{1-\varepsilon_b}{\varepsilon_b} k_f a_p (C_p - C) \qquad [1]$$

Equation 1 was subjected to the boundary condition:

$$\text{at } Z = 0,\ V_s = V_{si} \qquad \text{for all } t \qquad [1a]$$

Equations 1 and 1a were nondimensionalized by using $V'_s = V_s/V_{si}$, $t' = V_{si} \bullet t/L$ and $Z' = Z/L$. The resulting nondimensional equation simplified to:

$$\frac{dV'_s}{dZ'} = \frac{1-\varepsilon_b}{\varepsilon_b} (a_p L) \frac{Sh}{Pe_i} (C_p - C) \qquad [2]$$

Equation 2 was solved by using the boundary condition:

$$\text{at } Z' = 0,\ V'_s = 1 \qquad \text{for all } t' \qquad [2a]$$

Species continuity in the bulk phase. Along lines similar to the above and adopting the same nondimensionalizing scheme, the solute balance yielded:

$$\frac{\partial C}{\partial t'}+\frac{\partial(V'_sC)}{\partial Z'}=\frac{D_Z}{D_{Zi}}\frac{D_{Zi}}{D_{mi}}\frac{1}{Pe_iL}\frac{d_p}{L}\frac{\partial^2C}{\partial Z'^2}+\frac{1-\varepsilon_b}{\varepsilon_b})a_pL)\frac{Sh}{Pe_i}(C_p-C) \qquad [3]$$

Equation 3 was solved for the initial condition:

$$\text{at } t'=0,\ C=C, \qquad \text{for all } Z' \qquad [3a]$$

and boundary conditions:

$$\text{at } Z'=0,\ V'_sC-\left(\frac{D_Z}{D_{Zi}}\frac{D_{Zi}}{D_{mi}}\frac{1}{Pe_i}\frac{d_p}{L}\right)\frac{\partial C}{\partial Z}=C_i \ \text{ for all } t' \qquad [3b]$$

$$\text{and at } Z'=1,\ \frac{\partial C}{\partial Z'}=0 \ \text{ for all } t' \qquad [3c]$$

Species continuity in the pore phase. In nondimensional form, the equation for species continuity was:

$$\frac{dC_p}{dt'}[1+\frac{1}{\varepsilon_p}\frac{dN}{dC_p}]+\frac{1}{\varepsilon_p}\frac{Sh}{Pe_i}(a_pL)(C_p-C)=0 \qquad [4]$$

Equation 4 was solved for the initial condition:

$$\text{at } t'=0,\ C_p=C_{pi} \qquad \text{for all } Z' \qquad [4a]$$

Sherwood number (Sh) as per Treybal (8) is given by:

$$\begin{aligned} Sh &= 2.4\ Re^{0.34}Sc^{0.42} \text{ valid for } 0.08 < Re < 0.125 \\ &= 0.442\ Re^{0.69}Sc^{0.42} \text{ valid for } 0.125 < Re < 5000 \qquad [5a] \end{aligned}$$

and Peclet number as per Butt (9), by

$$\varepsilon_b \bullet Pe = 0.2 + 0.011\ Re^{0.48} \qquad [5b]$$

The Re and Sc were upgraded by means of the following equations:

$$Re = V_sd_p\rho_t/\mu_l = Re_iV'_s(\rho_t/\rho_{li})(\mu_{li}/\mu_l) \qquad [5c]$$

$$Sc = \mu_l/(\rho_lD_l) = Sc_i(\mu_l/\mu_{li})(\rho_{li}/\rho_l)(D_{li}/D_l) \qquad [5d]$$

where subscript "i" refers to initial state.

The viscosity ratio (μ_l/μ_{li}) and the diffusion coefficient ratio (D_l/D_{li}) were evaluated in a similar manner to Reid *et al.* (10). The density ratio (ρ_l/ρ_{li}) was evaluated based on experiments by Majumdar (11).

The equilibrium relationship between the residual oil content (N, in mass fraction) of marc and the concentration of oil (C_p, in mass fraction) of stagnant miscella in pores was obtained through experiments. Details of the experiment are provided by Majumdar (11). The relationship for the specific system of rice bran (as oil-bearing vegetable material) and hexane at 30°C was:

$$N = 0.2032 \bullet C_p \qquad [6]$$

The bran sample used had a total extractable oil of 20% (by weight) and a moisture content of 7% (wet basis).

The set of generalized nondimensional Equations 2 through 4, along with relevant initial conditions and boundary conditions, together with the equilibrium relationship Equation 6, constitute the proposed generalized model describing the behavior of packed-bed-type extractor. Equations 2 and 4 were solved with modified Euler's method, while Equation 3 was solved with the Crank-Nicolson algorithm (12).

RESULTS AND DISCUSSION

We recognized from the model that the nondimensional input parameters governing the process of extraction were initial Reynolds number (Re_i) based on particle diameter, initial Schmidt number (Sc_i), bed void volume (ε_b), particle porosity (ε_p), ratio of bed diameter to particle diameter (D_t/d_p), ratio of bed height to bed diameter (L/D_t), ratio of particle surface area to bed cross section (a_pL), initial oil concentration (C_i, in mass fraction) of the solvent, and the equilibrium distribution coefficient (EDC).

Effect of Re_i. A change in Re_i, while other parameters were held constant, meant that the throughput of solvent into the bed changed. Figure 2 presents the effect of Re_i on oil concentrations of bulk and pore miscellas at bed exit with time. While the oil concentration of the bulk phase rises to a peak value and then falls, the oil concentration of the stagnant phase falls continuously.

A higher rate of mass transfer was associated with a higher Re and was governed by Equation 5a involving Sh as a function of Re and Sc. Thus, a higher value of the peak oil concentration was attained with a higher Re_i. Although the location of the peak oil concentration was nearly the same on the nondimensional time scale, the actual time (dimensional) for the peak to appear with a higher Re_i was less than with a lower Re_i.

In the nondimensional scheme, the nondimensional time (t') was given by:

$$t' = (t \bullet V_{si})/L \qquad [7]$$

As mentioned earlier, a change in Re_i was associated with a change in throughput and, therefore:

$$(t_{Re1}/t'_{Re2}) = (t_{Re1}/t_{Re2})(V_{si(Re1)}/V_{si(Re2)}) \qquad [8]$$

The nondimensional times to attain peak concentration in bulk for various Re_i values were nearly the same, i.e., $t'_{Re1} \approx t'_{Re2}$. Therefore,

$$t_{Re2} = (V_{si(Re1)}/V_{si(Re2)})t_{Re1} \qquad [9]$$

As an example, for $Re_1 = 100$ and $Re_2 = 20$, $V_{si(Re\,=\,100)}/$

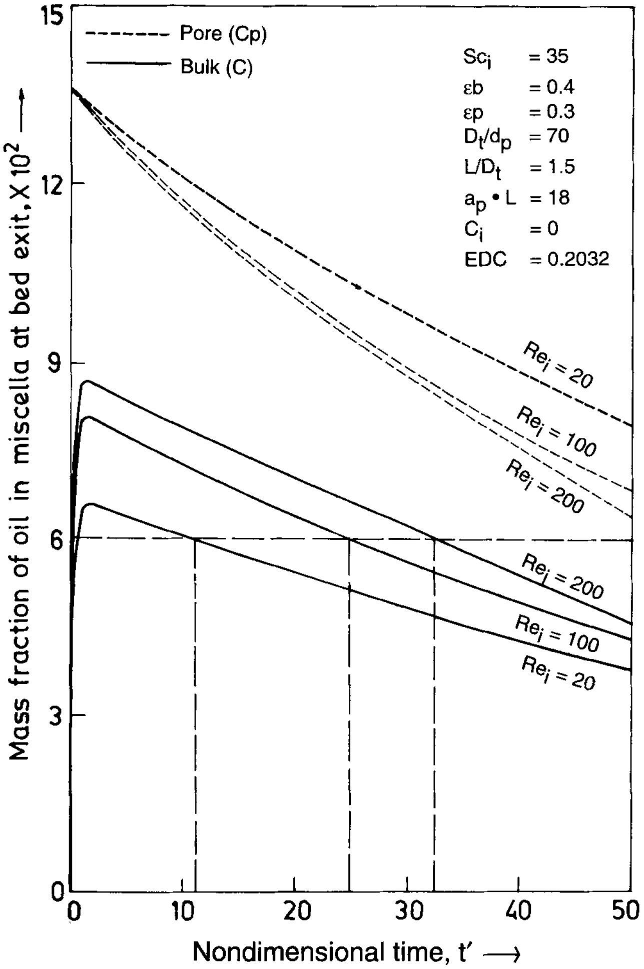

FIG. 2. Effect of initial Reynolds number (Re_i) on oil concentrations of bulk and pore miscellas at bed exit; Sc_i, initial Schmidt number; εb, bed void volume; εp, particle porosity; D_t/d_p, bed diameter to particle diameter ratio; L/D_t, bed depth to bed diameter ratio; $a_p \bullet L$, ratio of particle surface area to bed cross-section; C; initial oil concentration; EDC, equilibrium distribution coefficient.

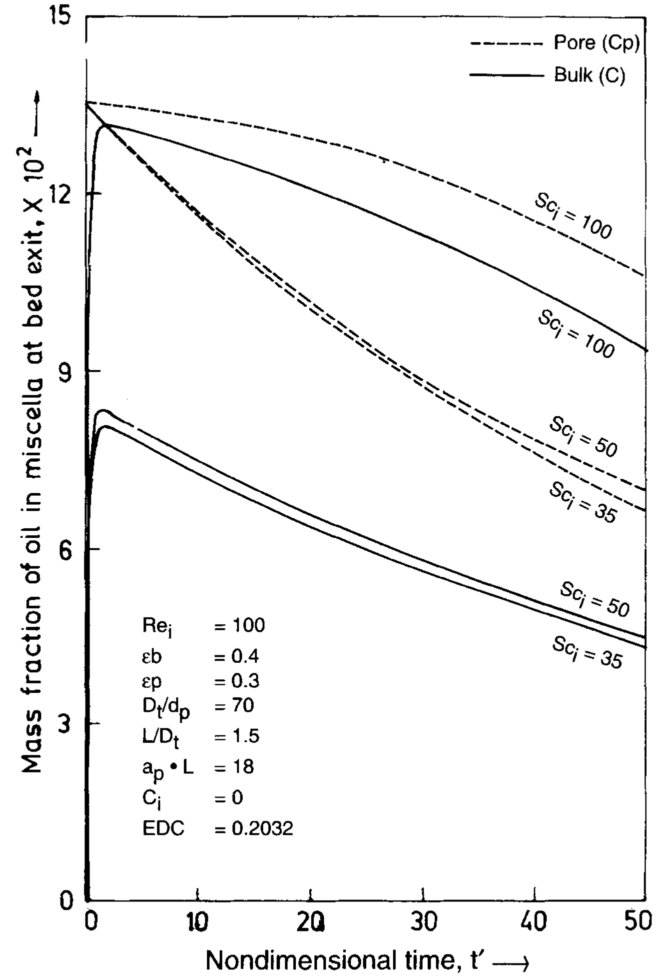

FIG. 3. Effect of Sc_i on oil concentrations of bulk and pore miscellas at bed exit. See Figure 2 for abbreviations.

$V_{si(Re=20)} = 5$, and therefore, $t_{Re2(Re=20)} = 5t_{Re1(Re=100)}$. The above analysis substantiated that the dimensional time (t) for the peak to appear for a higher Re_i was less than for a lower Re_i.

Through a similar analysis, we concluded that, to attain the same concentration of oil in bulk miscella at bed exit, the actual time (dimensional) required for a higher Re_i was less than that for a lower Re_i. A higher Re_i was also associated with a lower pore phase concentration, which indicated lower residual oil content in the marc.

Further, from Figure 2, the driving force ($C_p - C$) available for mass transfer for the same oil concentration of miscella in pores was higher at a lower Re_i. It is known that Sc is of the order of the ratio of momentum boundary layer to concentration boundary layer thickness. Therefore, with a higher Re_i, the gradients associated with momentum transfer (i.e., $\partial V_s/\partial Z$) and mass transfer ($\partial C/\partial Z$) were steeper and associated with higher transfer rates at any point of time. From the above, we concluded that a higher Re_i was associated with a lower oil concentration of stagnant miscella in pores and a higher oil concentration of bulk miscella.

To summarize: (i) a higher Re_i resulted in a higher oil concentration of bulk miscella; (ii) a higher Re_i resulted in a lower oil concentration of stagnant miscella in pores; and (iii) a higher Re_i resulted in a lower concentration difference (C_p–C) between bulk and pore phase miscellas over time. We conclude that, in order to extract to a specific residual oil content of the marc, increasing Re_i reduced the time required for extraction.

Effect of Sc_i. Sc_i is defined as the ratio of momentum diffusivity to mass diffusivity. It may also be defined as the order of momentum transport boundary layer to mass transport boundary layer thicknesses.

Figure 3 presents the effect of Sc_i on oil concentrations of bulk and pore miscellas at bed exit with time. It could be observed from the figure that (i) a higher Sc_i was associated with a higher oil concentration of the miscella in both the bulk and pore phases; (ii) a higher Sc_i was also associated with a lower oil concentration difference between the bulk and pore phase miscellas; and (iii) for the range of Sc_i values studied, the peak oil concentration of the bulk occurred at the same time (nondimensional).

A higher Sc_i, being associated with a higher momentum diffusivity, resulted in rapid mass transport as compared with a lower Sc_i. Convective mass transport appeared to be dominant over diffusive mass transport for a higher Sc_i. This trend was more prominent because of the linear equilibrium relationship exhibited by the system. Convective transport was therefore responsible for a lower oil concentration difference ($C_p - C$) between the miscellas in pore and bulk phases at higher Sc_i. For lower Sc_i, in which the convective transport was lower, the oil released by the solids to the stagnant miscella in pores (as governed by the equilibrium relationship) was not easily convected away by the bulk phase. This resulted in a larger oil concentration difference between the two phases.

A higher Sc_i could also be construed as being associated with a lower concentration boundary layer thickness and, hence, with a steeper concentration gradient, resulting in higher mass transfer rate (Re_i remaining constant, the momentum boundary layer thickness was unaltered). Figure 3 shows that, for $Sc_i = 100$, the mass diffusivity was lower by an order of magnitude compared with momentum diffusivity, the concentration difference between miscellas in pore and bulk phases became lower, and the oil in the pores was not quickly released to the bulk phase.

We conclude from the study that it was not beneficial to extract oil with solvents whose momentum diffusivity was much higher compared with the mass diffusivity for systems exhibiting equilibrium relationship as considered in the present study. The effect of bed temperature could be visualized through a change in Sc_i because diffusivities are functions of temperature.

Effect of ε_b. The effect of ε_b was studied through the nondimensional parameter identified in Equations 2 and 3 as $(1-\varepsilon_b)/\varepsilon_b$, which could be written as:

$$(1-\varepsilon_b)\varepsilon_b = [\text{solid volume/void volume}] = [n_p/\{1.5\,(D_t/d_p)^3(L/D_t) - n_p\}] \qquad [10]$$

where n_p = number of particles of size d_p, D_t = bed diameter, and L = bed depth.

Therefore, a variation in $(1-\varepsilon_b)/\varepsilon_b$, in effect, indicated a variation in the number of particles (n_p), where D_t/d_p and L/D_t were held constant. An increase in the number of particles increased $(1-\varepsilon_b)/\varepsilon_b$, which meant that more material was available for extraction. Again, an increase in $(1-\varepsilon_b)/\varepsilon_b$ meant a decrease in ε_b. The result has been discussed subsequently in terms of variation in ε_b.

Higher ε_b meant less quantity of solids and, hence, less quantity of oil available in the bed for extraction and *vice versa.* Figure 4 shows the effect of ε_b on oil concentrations of bulk and pore miscellas at bed exit with time. With an increase in ε_b, the peak oil concentration in the bulk miscella at bed exit decreased because less oil was available. Similarly, the oil concentration of pore miscella at bed exit became lower at any point of time. Further, with an increase in ε_b, the *interstitial* velocity decreased, leading to lower local Re, which ultimately decreased the rate of mass transfer of oil from pores to bulk. Thus, the higher the ε_b, the higher was the oil concentration difference between miscellas in process and the bulk at any point of time. Peclet number (Pe) (which governs axial dispersion) also has a bearing on ε_b as per Equation 5b.

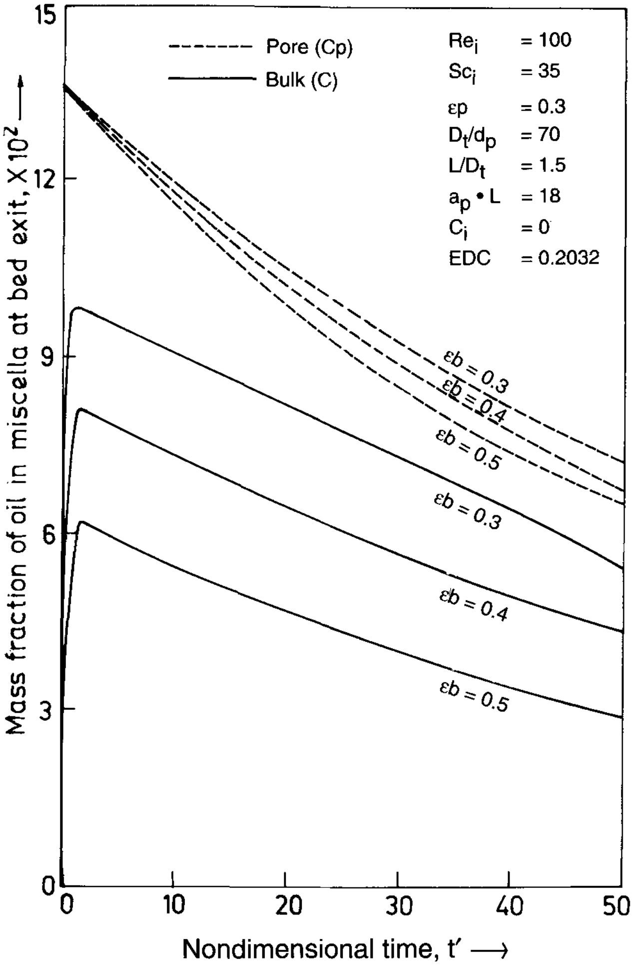

FIG. 4. Effect of ε_b on oil concentrations of bulk and pore miscellas at bed exit. See Figure 2 for abbreviations.

Lower ε_p was associated with higher bed loading, consequently more time was required to reach a specific oil concentration of bulk miscella. Because Re_i and other pertinent parameters were held constant, the peak oil concentration of bulk miscella occurred at the same time for the range of ε_b values studied.

Effect of ε_p. Other parameters remaining constant, a change in ε_p indicated a change in the fraction of solids in the particle. A higher ε_p resulted in a lower fraction of solids in the particle. Figure 5 shows the effect of ε_p on oil concentrations of bulk and pore miscellas at bed exit with time.

The residual oil content per unit mass of marc, expressed in mass fraction, was:

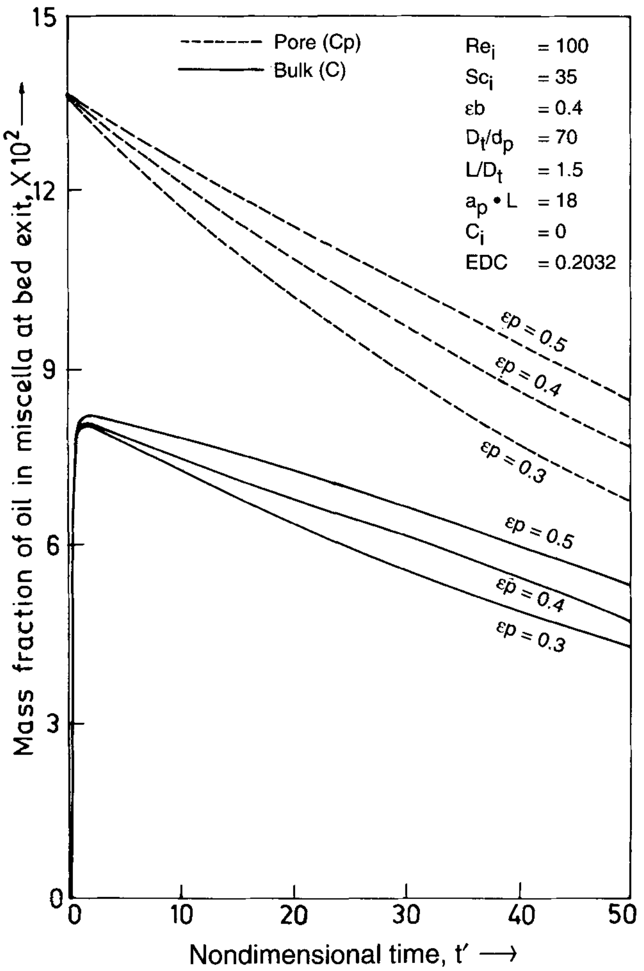

FIG. 5. Effect of ε_p on oil concentrations of bulk and pore miscellas at bed exit. See Figure 2 for abbreviations.

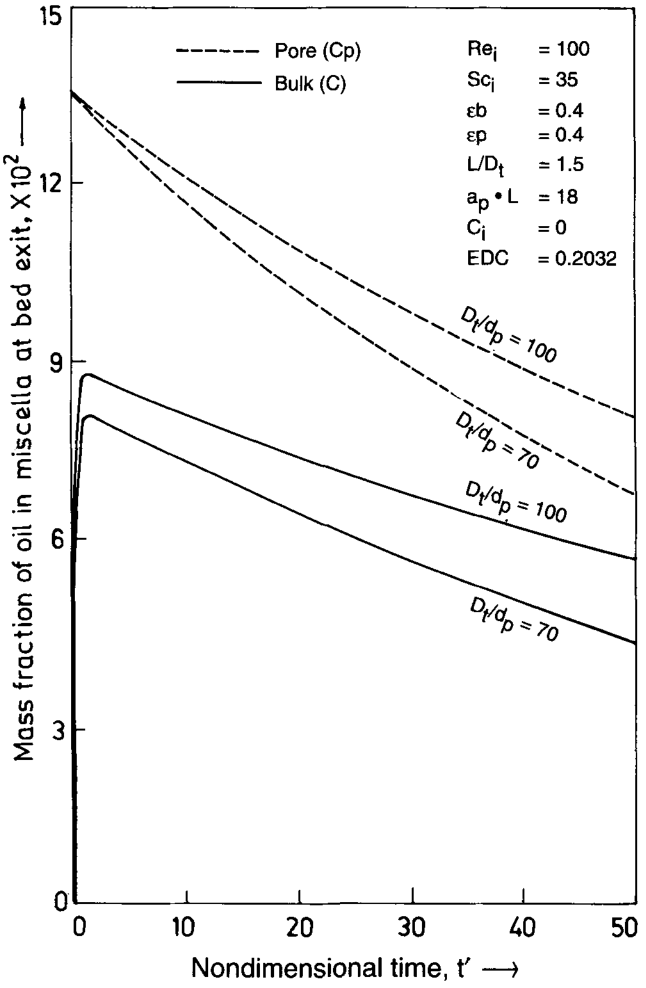

FIG. 6. Effect of D_t/d_p on oil concentrations of bulk and pore miscellas at bed exit. See Figure 2 for abbreviations.

N = mass of residual oil in marc/mass of marc
= mass of residual oil/(mass of oil-free solids + mass of residual oil)
= volume of residual oil ρ_{oil}/(volume of oil-free solids ρ_{bs} + volume of residual oil ρ_{oil}) [11]

where ρ_{oil} = density of oil, and ρ_{bs} = bulk density of oil-free solids.

In other words, the volume of solids was inclusive of ε_p and was linked through ρ_{bs}. Therefore, a change in ε_p should alter the equilibrium relationship (N vs. C_p). However, as the mass fraction of oil per unit mass of marc was unaltered for the present case, a higher ε_p indicated a higher oil content resident per unit volume of oil-free solids (when all other parameters were held constant). Therefore, a higher ε_p, being associated with a reduced fraction of solids in the particle, resulted in increased oil concentrations of miscellas in both the bulk and pore phases.

Also, the degree of change in the oil concentration of the stagnant miscella in pores was of the same order of magnitude as that of the bulk phase. Axial dispersion through Pe and mass transfer rate through Sh were affected only by ε_b and not by ε_p.

Particle porosity affected the equilibrium relationship directly because an increase in total oil resident in solids was associated with higher ε_p, as shown in Equation 11. Thus, higher ε_p resulted in more time for extraction to a specific oil concentration of bulk miscella and was also associated with a higher peak concentration.

Effect of D_t/d_p. Varying D_t/d_p, while holding other parameters constant, was associated with a change in D_t (d_p could not be changed without changing Re_i). An increase in D_t/d_p indicated an increase in D_t. One of the nondimensional parameters recognized in the course of model development was (L/D_t) ratio. If D_t was altered, the bed depth (L) had to be correspondingly altered to keep the L/D_t constant while varying D_t/d_p.

Figure 6 shows the effect of D_t/d_p on oil concentrations of bulk and pore miscellas at bed exit with time. Increasing D_td_p increased the solids loading in the bed. Because of increased D_t and the resulting proportional increase in L, more oil was available for extraction. Thus, with increase in D_t/d_p, the oil

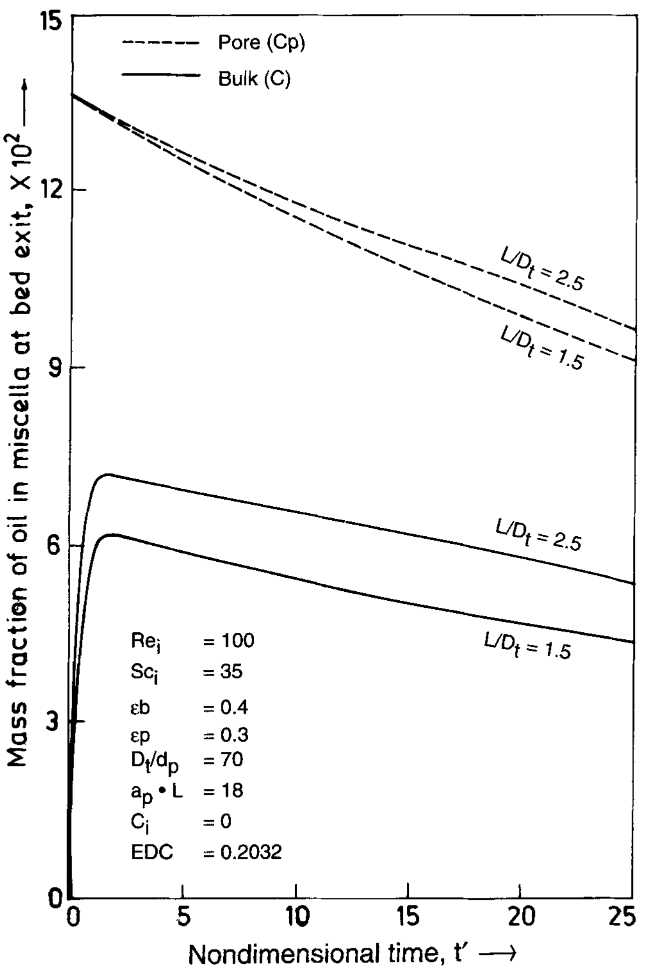

FIG. 7. Effect of L/D_t on oil concentrations of bulk and pore miscellas at bed exit. See Figure 2 for abbreviations.

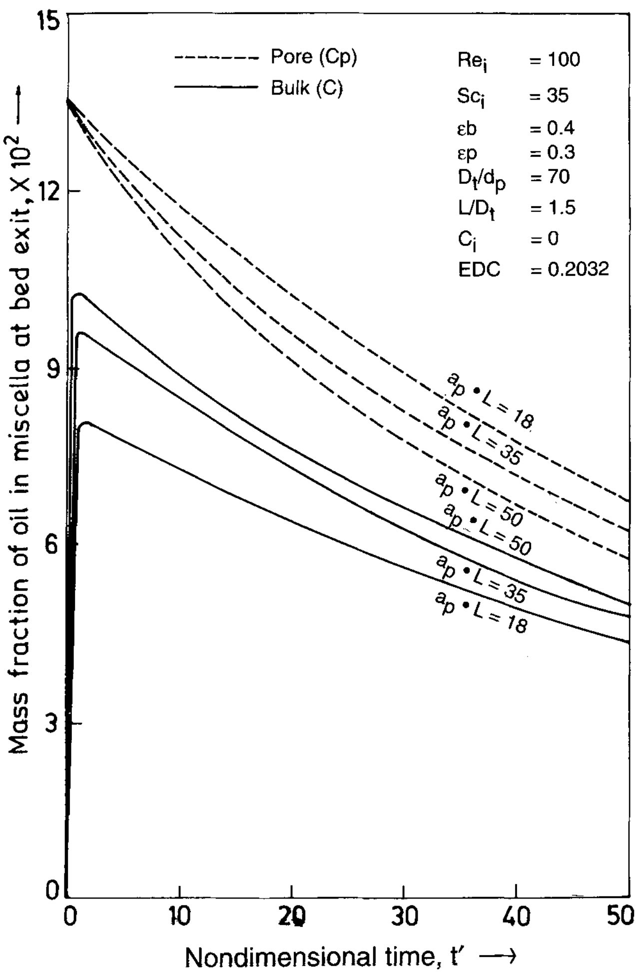

FIG. 8. Effect of a_pL on oil concentrations of bulk and pore miscellas at bed exit. See Figure 2 for abbreviations.

concentration of bulk miscella (at bed exit) reached a higher peak. As D_t/d_p increased, resulting in increased solids loading in the bed, it took more time for extraction to a specific oil concentration of bulk miscella.

Effect of the L/D_t. Changing L/D_t, while keeping other parameters constant, was in effect changing L. An increased L/D_t ratio was associated with higher solids loading and a corresponding greater amount of oil available for extraction.

Figure 7 presents the effect of L/D_t on oil concentrations of bulk and pore miscellas at bed exit with time. As expected, a higher L/D_t was associated with a higher peak concentration of bulk miscella at bed exit. The trend presented in this figure could be explained along similar lines provided for D_t/d_p.

Effect of a_pL. Particle surface area to bed cross-section ratio led to the nondimensional parameter a_pL. Variation in a_pL, while keeping other parameters constant, indicated a variation in the particle surface area (per unit volume of the particle) across which mass transfer (of oil) took place. Higher a_pL, therefore, meant more surface area was available (for the same volume of particles) for mass transfer and, hence, a higher quantity (mass) of oil was transformed from the stagnant miscella in pores to the bulk miscella.

Figure 8 presents the effect of a_pL on oil concentrations of bulk and pore miscellas at bed exit with time. At higher a_pL, because of the larger mass of oil transferred from pores to the bulk through diffusion, the oil concentration of the bulk miscella at any point in time was higher. This led to a lower oil concentration of miscella in pores.

Effect of recycled miscella. Recycling miscella meant a continuous time rate of change of its oil concentration while it was fed back to the inlet of the bed. Figure 9 presents two cases that illustrate the effect of varying the oil concentration of solvent/miscella input to the bed on oil concentrations of bulk and pore miscellas at bed exit with time. In one case, the input to the bed was always a fresh solvent, which means that the oil concentration of the input solvent for all time is nil, that is, $C(0,t) = 0$. In the other case, the miscella that was leaving the bed was recycled back to the inlet of the bed, that is, $C(0,t) = C(L,t-\Delta t)$. In the latter case, the miscella, which already contained oil, picked up more oil from the bed as it flowed down through the packed bed. Hence, at any point in

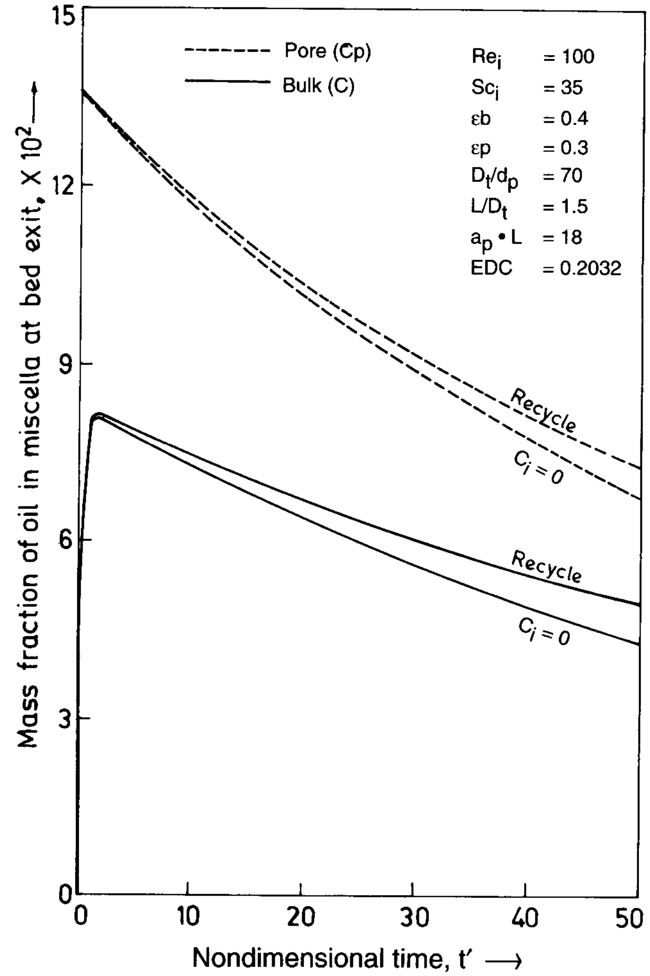

FIG. 9. Effect of recycle on oil concentrations of bulk and pore miscellas at bed exit. See Figure 2 for abbreviations.

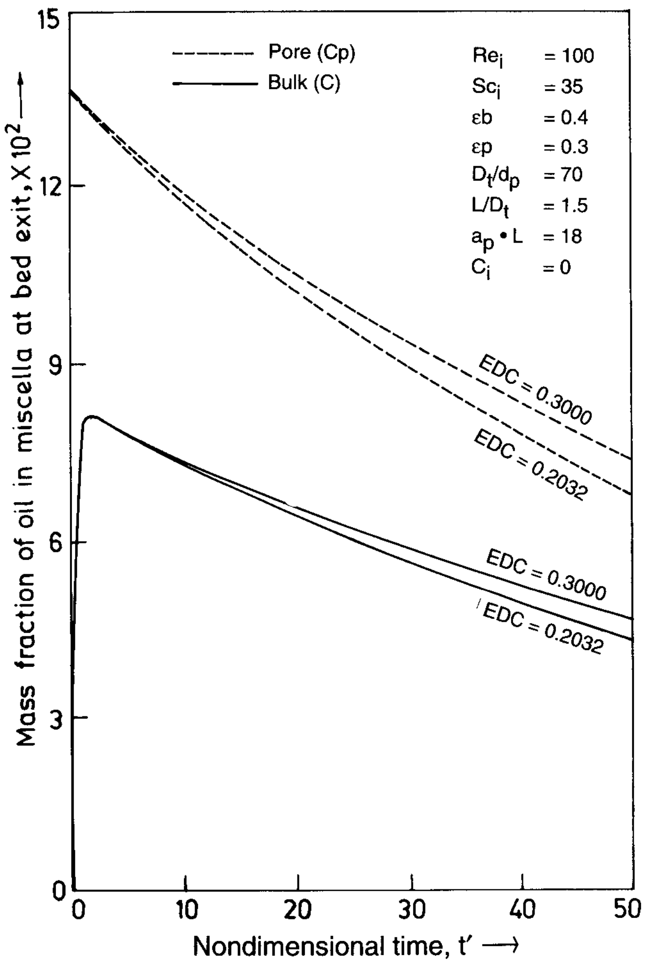

FIG. 10. Effect of EDC on oil concentrations of bulk and pore miscellas at bed exit. See Figure 2 for abbreviations.

time (Re_i remaining constant, the nondimensional and dimensional time were identical), the oil concentration of the bulk miscella with recycle was higher than that with fresh solvent. Additional observations that could be made from the graphs were: (i) the rate of fall of C_p with recycle was slower than that with fresh solvent; (ii) the rate at which (C_p – C) changed was slower with recycle than with fresh solvent; (iii) it took longer to reach a specific residual oil content of marc with recycle than that with fresh solvent; and (iv) recycle caused a higher peak oil concentration of bulk miscella.

Effect of EDC. EDC was defined as the ratio of residual oil content of marc to the oil concentration of the stagnant miscella in pores at equilibrium. A higher EDC was associated with higher residual oil content (N) of the marc, which, in turn, meant lower oil extraction from solids. In other words, a higher EDC indicated a higher degree of difficulty in extracting oil from the oil-bearing solids.

Figure 10 presents the effect of EDC on oil concentrations of bulk and pore miscellas at bed exit with time. When EDC was high, it took a longer time to achieve the same oil concentration of bulk miscella at bed exit compared with low EDC. With high EDC, N at any point in time was high, as observed from the high C_p value in the figure. Given that the ratio of densities (p_s/p_l) and N remained unaltered, a high EDC resulted in low C_p.

A change in EDC could also be viewed as: (i) changing the oil-bearing material and solvent system, or (ii) changing the extraction temperature.

Conclusions. In terms of the time required for the process of extraction to reach a specific residual oil content in the marc, the following conclusions were drawn from the study: (i) Higher Re_i was associated with less time for extraction (while the oil concentration of bulk miscella at bed exit was rising to a peak value, the same of the stagnant miscella in pores was more or less constant); (ii) lower Sc_i was associated with less time for extraction; and (iii) of the parameters that either had little influence or could not be significantly changed, higher values of ε_b and a_pL and lower values of ε_p, D_t/d_p, L/D_t, and EDC were associated with less time for extraction.

REFERENCES

1. Fan, H.P., and J.C. Morris, *J. Am. Oil Chem. Soc. 40*:195 (1948).
2. Lee, A.K.K., N.R. Bulley, M. Fattori and A. Meisen, *Ibid. 63*:921 (1986).
3. Karnofsky, G., *Ibid. 63*:1011 (1986).
4. Abraham, G., R.J. Hron and S.P. Koltum, *Ibid. 65*:129 (1988).
5. Chien, J.T., J.E. Hoff, M.J. Lee, H.M. Lin, Y.J. Chen and L.F. Chen, *Chem. Eng. J.* 43:103 (1990).
6. Karnofsky, G., *J. Am. Oil Chem. Soc. 63*:1011 (1986).
7. Karnofsky, G., *Ibid. 64*:1533 (1987).
8. Treybal, R.E., *Mass-Transfer Operations*, McGraw-Hill Kogakusha Ltd., Singapore, 1981.
9. Butt, J.B., *Reaction Kinetics and Reactor Design*, Prentice Hall, New Jersey, 1980.
10. Reid, R.C., J.M. Prausnitz and B.E. Polling, *The Properties of Gases and Liquids*, McGraw-Hill International Edition, Singapore, 1988.
11. Majumdar, G.C., Theoretical Studies on Some Aspects of Solvent Extraction of Vegetable Oil in a Packed Bed, Ph.D. Thesis, Indian Institute of Technology, Kharagpur, India, 1993.
12. Anderson, D.A., J.C. Tannehill and R.H. Pletcher, *Computational Fluid Mechanics and Heat Transfer*, Hemisphere Publishing Corporation, Washington DC, 1984.

[Received April 2, 1994; accepted May 10, 1995]