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A shrinking core model for seeds oil extraction with particularization to Camelina oil separation

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ABSTRACT

The oil extraction from a spherical particle in an adequate solvent is analyzed by a dynamic model. The oil extraction occurs by moving the unsolubilized solid/solute-free phase interface toward the center of the particle. We assume that the transport of solute molecules has three resistances: (1) the resistance due to oil core dissolving; (2) the resistance due to the solute-free portion of the particle; (3) the resistance due to a surface layer near solid–liquid interface. Generally, the equation governing the dynamic behavior of oil extraction is numerically solved. However, sometimes analytical expressions for the time dynamics of the size of the unsolubilized oil portion can be obtained in some special cases. The present analysis on oil process extraction takes into account the effect of variable bulk solute concentration and of seed internal characteristics such as particle porosity, particle tortuosity and core oil dissolving kinetics. Result consists in a general mathematical model whose particularization is given for the case of Camelina seeds oil extraction. For Camelina seeds the oil hexane extraction has been characterized by particularization of the general modified shrinking core model. It has obtained that the particle dimensionless porosity is set to 0.08, while the constant of kinetic process from the shrinking core surface is strongly dependent on core position and on the temperature after relation $k_d = k_{d0}(t)(r_c/R)^n$ with $n = 4$ and $k_{d0}(t)$ in the range 4.3–8.3 10^{-8} m/s.

1. Introduction

The engineering and design processes for a production line which extracts oil from seeds must to take into account many factors. The major concern is to design a process that will achieve a high return of investment. Proper design considers the individual characteristics of the primary raw material and provisions for adoption to oil extraction from allied seeds and processing. The choice of one or the other process is, ultimately, determined by the volatility of extract and the propensity of the extract to turn rancid through oxidation. Proper choice of the oil pressing, extraction and refining process can greatly improve the quality and yield as well as the unit production cost. Two rules have been established in time: (i) high oil content seeds adopt pre-pressing and extraction; (ii) low oil content seeds adopt direct oil extraction. For designing of an extraction device, knowing the extraction kinetics is essential. If experimental kinetics is used, it cannot proceed to a deep process optimization because the parameters characterizing the extraction kinetics are not disposable. In order to optimize the extraction operating conditions to achieve maximum oil extraction percentage, the effect of five main factors should be considered. These factors are: type of solvent, temperature, solvent to solid ratio, particle size of the meal and oil content of the seed are important. The factors also appear in various models (Betiku and Adepoju, 2013; Aloko et al., 2013; Topallar and Gecgel, 2000; Kumhoma et al., 2011; Crisan et al., 2013) used for extraction kinetics characterization. By means

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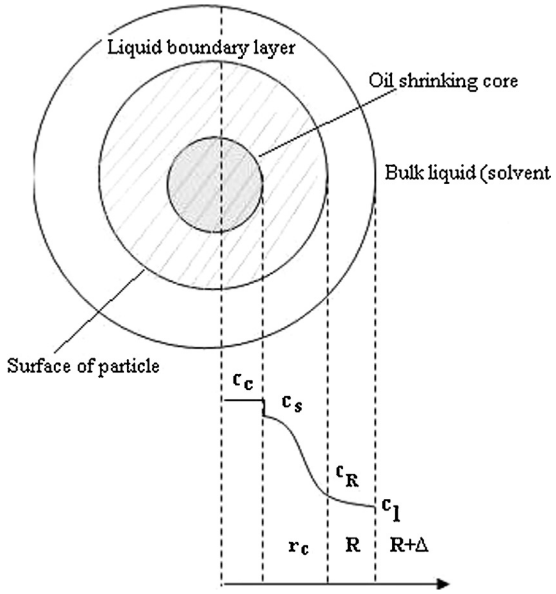

Fig. 1 – The schematic representation of oil extraction from a porous spherical seed.

of a modified shrinking core model, the present paper tries to show the effect of the mentioned factors on oil extraction kinetics from ground or non-ground seeds. The proposed model for solvent extraction refers to both diffusion in the solid matrix and convection in the surrounding liquid miscella and introduces a kinetic process at the surface of the shrinking oil core.

2. The modified shrinking core model

The basic principle of the shrinking core model of oil extraction from a spherical particle is introduced by Fig. 1. The assumption is that a surface layer near the surface of a spherical particle exists. Also, the solvent dissolving of oil yields a solute-free vegetal (solid) phase on the outer portion of the particle. As solvent oil dissolving proceeds, the interface between the non-dissolved oil from solid phase and the solute-free solid phase moves toward the center of the particle. The novelty of the modified shrinking core model consists in the fact that the oil solvent dissolution consists of four steps in series: (i) oil (solute) dissolving in the solvent at core level; (ii) diffusion of solute molecules from the oil-vegetal structure (solid) interface through the solute-free portion of the particle to the solid–liquid interface; (iii) diffusion of solute molecules from the solid–liquid interface through the surface layer to the outer boundary; (iv) diffusion of solute molecules from the outer boundary of the surface layer to bulk liquid phase. The concentration of solute on the solid–solid interface is supposed to be in the saturation vicinity, if it exists. Based of the above mentioned considerations, the oil balance over oil free portion of the particle and solvent boundary layer is described by relation (1) and (2), respectively.

Here c is momentary local oil concentration whereas D_{ep} and D_l represent the oil effective diffusion coefficient in particle and oil diffusion coefficient in the extraction solvent, respectively.

$$\frac{\partial c}{\partial \tau} = \frac{D_{ep}}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial c}{\partial r}\right), \quad r_c < r < R \tag{1}$$

$$\frac{\partial c}{\partial \tau} = \frac{D_l}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial c}{\partial r}\right), \quad R < r < R+\Delta \tag{2}$$

If the diffusion rate of solute is much greater than the rate of moving of the core interface toward the center of the particle, then a pseudo-steady state can be assumed. In this case (1) and (2) generate the following diffusion problems:

$$\frac{D_{ep}}{r^2}\frac{dc}{dr}\left(r^2\frac{\partial c}{\partial r}\right), \quad r_c < r < R,\ r = r_c \Leftrightarrow c = c_s,\ r = R \Leftrightarrow c = c_R \tag{3}$$

$$\frac{D_l}{r^2}\frac{dc}{dr}\left(r^2\frac{\partial c}{\partial r}\right), \quad R < r < R+\Delta,\ r = R \Leftrightarrow c = c_R,\ r = R+\Delta \Leftrightarrow c = c_l \tag{4}$$

The solution of these equations (5)–(8) and the flux continuity at particle surface (9) give the link between particle surface oil concentration versus oil concentration outside of boundary layer and near to shrinking core (10).

$$c(r) = c_s - \left(\frac{1}{r_c} - \frac{1}{r}\right)\frac{c_s - c_R}{((1/r_c) - (1/R))} \quad r_c < r < R \tag{5}$$

$$\frac{dc}{dr} = \frac{1}{r^2}\frac{c_s - c_R}{((1/r_c) - (1/R))} \quad r_c < r < R \tag{6}$$

$$c(r) = c_R - \left(\frac{1}{R} - \frac{1}{r}\right)\frac{c_R - c_l}{((1/R) - (1/R+\Delta))} \quad R < r < R+\Delta \tag{7}$$

$$\frac{dc}{dr} = \frac{1}{r^2}\frac{c_R - c_l}{((1/R) - (1/R+\Delta))} \quad R < r < R+\Delta \tag{8}$$

$$D_{ep}\left(\frac{dc}{dr}\right)_{\substack{r=R\\ r\le R}} = D_l\left(\frac{dc}{dr}\right)_{\substack{r=R\\ r\ge R}} \tag{9}$$

$$c_R = \frac{\frac{D_l}{D_{ep}}c_l\left(\frac{1}{R} - \frac{1}{R+\Delta}\right) + c_s\left(\frac{1}{r_c} - \frac{1}{R}\right)}{\frac{D_l}{D_{ep}}\left(\frac{1}{R} - \frac{1}{R+\Delta}\right) + \left(\frac{1}{r_c} - \frac{1}{R}\right)} \tag{10}$$

For c_s from the above relations, there are two cases identified. If the solubility of oil in the solvent is limited (normally dependent on temperature) then c_s can be in the vicinity of oil saturation concentration. This is an exception case because the practice has imposed a total solubility of the oil in extraction solvent. In this case the c_s value targets the core oil concentration (c_c). It is difficult to accept that at core surface is not a resistance to oil dissolving because here the extraction occurs at cell level. On the other hand, the winding of cell chains forming seed (particle) is getting close to its interior. So the intensity of core dissolving will depend on their position in seed. As a consequence, at surface of the shrinking core, we assume that the oil dissolving is controlled by a kinetic process, which has the first order corresponding to the concentration excess (c_c–c_s in Fig. 1).

Specifically, the oil flux continuity, shown in relation (11), is used, where k_d is the local constant of kinetic process characterizing the oil dissolving.

$$D_{ep}\left(\frac{dc}{dr}\right)_{r=r_c} = k_d(c_c - c_s) \tag{11}$$