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Mathematical modeling of vegetable oil extraction in a counter-current crossed flow horizontal extractor

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Abstract

In this work a new mathematical model of vegetable oil extraction in an industrial "De Smet" type extractor is proposed to predict the concentration distributions in percolation sections and at the outlets. Oil losses are also considered. The model incorporates counter-current crossed flow of the porous media and the miscela, mass transfer between the expanded flakes and the miscela, diffusion in the entire extraction field, miscela transport between the percolation sections, influence of loading and drainage zones, and transient operational regimes of the extractor. The model is composed of sub-models for the percolation sections, trays, drainage and loading zones. The sub-models are coupled to each other by means of the boundary conditions, and reflect the particularities of counter-current flow. The calculation algorithm is based on the method of lines. The variations in concentration distributions of bulk and pore phases, and their properties, such as: waves, slopes, steps, etc., are presented.

Keywords: Mathematical model; Food processing; Counter-current crossed flow; Oil extraction; Porous media

1. Introduction

Industrial vegetable oil extractors such as "De Smet", "Rotocell" and "Crow Model" have been used in the food industry for more than 20 years (Bockisch, 1998). In their extraction fields, the expanded flakes (a porous media) and the miscela (a liquid that extracts oil from the flakes) interact through counter-current cross (CCC) flows (Bockisch, 1998; Miyasaka & Medina, 1981). Mathematical models of CCC flows, different of other flow configurations [e.g., co-current flow (Iliuta & Thyrion, 1997), counter-current flow (Lasseran & Courtois, 1993), crossed flow (Qi & Krishnan, 1996)], have not been elaborated yet. In the design and process simulation of extractors, different versions of the multi-stages method are extensively used when, for each percolation section, a uniform oil distribution concentration is assumed in each component (Foust, Wenzel, Chump, Maus, & Anderson, 1982). This method, in its basic approach, is not sensitive to section dimensions, components velocities, and porous media porosities. Therefore, a great volume of experimental data that demand considerable expense and time accompanies the design and operation of the extractors. In this sense, a mathematical model of CCC flows that incorporates the diffusion laws and mass transfer, with spatial distribution of concentrations in the extraction field, is of great interest. Karnofsky (1986) observed that: "Nevertheless, plant operators should find useful a method that predicts the distribution of miscella concentrations in a commercial extractor. When they are experiencing mysterious operation problems, comparing their distribution with that predicted may give the clue to the source of trouble". Applied mathematical models to predict vegetable oil extraction were first proposed in the 1950s. Karnofsky (1949) and Coats and Karnofsky (1950) established a physical scheme of oil extraction from laminated flakes. In that work the experimental data was presented for different oleaginous species with different flake thicknesses. The mechanism of extraction

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Nomenclature

a_p	contact surface between the pore and the bulk phases per unit of volume (1/m)
C	oil concentration in the bulk phase (dimensionless)
C_{in}	oil concentration inside the solvent, tube 2, Fig. 1 (dimensionless)
$\overline{C}_m$	oil media concentration in mth tray (dimensionless)
C^N	oil concentration of the solid phase (dimensionless)
C^p	oil concentration in the pore phase (dimensionless)
C_s	initial volumetric concentration in solid phase (dimensionless)
C_u	miscela volumetric concentration in the extractor exit: Fig. 1, tube 5 (dimensionless)
d_p	average diameter of the flake particles (m)
D_{AB}	molecular mass diffusivity in the bulk phase (m^2/s)
E_d	equilibrium mass coefficient between the solid and pore phases (dimensionless)
E_d^v	equilibrium volumetric coefficient between the solid and pore phases (dimensionless)
E_s	dispersion coefficient (m/s)
g	oil mass fraction (dimensionless)
h	integration step (m)
H	thickness of the bed (m)
k_f	mass transfer coefficient between the pore and the bulk phases (m/s)
L_s	height of the porous media layer (m)
m_s	number of extractor sections (dimensionless)
M_n	mass flow rate of porous media in the extractor (kg/s)
N_t	initial oil mass fraction in the flakes (dimensionless)
Q_D	flow rate from the drainage zone to the tray (m^3/s)
Q_{es}	volumetric oil flow rate in the extractor inlet (m^3/s)
Q_f	oil flow rate lost from the extractor (m^3/s)
Q_h	volumetric horizontal flow rate of the bulk phase through section (m^3/s)
Q_p	miscela flow rate into the loading zone (m^3/s)
Q_q	solvent flow rate in the extractor inlet (m^3/s)
Q_s	miscela flow rate in the extractor exit (m^3/s)
Q_T	miscela vertical volumetric flow through section (m^3/s)
S_u	Courant number for flakes flow (dimensionless)
S_v	Courant number for miscela (dimensionless)
u	horizontal velocity of porous media (m/s)
u_h	miscela velocity in the horizontal direction (m/s)
V_b	tray oil volume (m^3)
V_m	miscela vertical velocity in the percolation section (m/s)
V_s	relatived velocity between the miscela and the porous media (m/s)
x	horizontal coordinate (m)
X_1	width of the first section (m)
X_f	left edge horizontal coordinate, AF, of the extraction field (m)
X_s	width of a typical section (m)
z	vertical coordinate (m)

Greek letters

Δx	horizontal cell dimension (m)
Δz	vertical cell dimension (m)
ε_b	outer porosity of the porous media, bulk phase (dimensionless)
ε_m	part of pore phase to occupy by miscela, Fig. 4 (dimensionless)
ε_p	internal porosity of the porous media, pore phase (dimensionless)
μ_m	miscela viscosity (Pa s)
ρ_{he}	solvent (hexane) density (kg/m^3)
ρ_m	miscela density (kg/m^3)
ρ_{ol}	oil density (kg/m^3)
ρ_s	solid phase density of porous media (kg/m^3)
τ	time (s)

Subscripts

0	initial
in	initial
ms	last section

Superscripts

N	solid phase
p	pore phase

appears to be a combination of diffusion, dialysis, and mixing of slowly soluble extractible material. Karnofsky (1986) also proposed a semi-empirical model of oil extraction in industrial extractors. The model uses as a basis the results of experimental tests developed in laboratories and then, by means of simple numerical treatments, predicts oil losses in industrial extractors.

In Abraham, Hron, and Koltun (1988), a coupled mathematical model of an extractor and other equipment (desolventizer (DT), miscela separator, etc.) was developed. The model included algebraic balance equations for each flow component (marc, water, oil and solvent) considering the equilibrium between the phases. The sub-model of the extractor itself was based