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Supercritical CO_2 oilseed extraction in multi-vessel plants. 2. Effect of number and geometry of extractors on production cost

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ABSTRACT

The objective of this work was to study production costs for the supercritical CO_2 extraction of a prepressed oilseed (packed bed with 2-mm particles) in a 2-m^3 industrial multi-vessel plant operating at 40 °C and 30 MPa, using a fully predictive mass transfer model to simulate the process. We modified the inner diameter ($47.3 \leq D \leq 65.6$ cm) and number ($n = 2, 3,$ or 4) of extraction vessels, and the mass flow rate of CO_2 ($Q = 3000$ or 6000 kg/h), thus changing the aspect ratio of the extraction vessels ($3 \leq L/D \leq 8$), and superficial velocity ($2.71 \leq U \leq 10.8$ mm/s) and specific mass flow rate ($6 \leq q \leq 24$ kg/h per kg substrate) of CO_2. Production cost decreased when increasing the mass flow rate of CO_2 or the number of extraction vessels (or when increasing q). Production cost did not depend on the geometry of extraction vessel for a constant specific mass flow rate of CO_2, but it decreased with a decreasing of the L/D ratio of the vessel for a constant superficial velocity of CO_2. For any given plant, the contribution of fixed cost items (capital, labor) to the production cost increased with extraction time, unlike that of variable cost items (substrate, CO_2, energy), which decreased. Thus, there was an optimal extraction time that minimized production cost for each plant. This work proposes an expression for capital cost of an industrial multi-vessel plant as a function of the mass flow rate of CO_2 (which defines the cost of the solvent cycle of the plant), and the volume of the extraction vessels (which together with number of extraction vessels define the cost of extraction section of the plant), with a scaling factor of 0.48 for both items. Under optimal conditions, capital cost represented 30–40% of the production cost, but uncertainties in capital cost estimates (about ±50% using the proposed expression) may largely affect these estimates. The lowest production cost estimated in this work was USD 7.8/kg oil for the extraction of prepressed oilseed in a four-vessel plant using 6000 kg/h of CO_2. The mass flow rate of CO_2 and number of extraction vessels also affected annual productivity that was about 360 ton oil for the same plant operating 7200 h per year. Oil yields were above 90% for both three- and four-vessel plants.

1. Introduction

The decision to apply supercritical fluid (SF) extraction [1] to commercially recover high-value compounds from selected biological substrates demands accurate cost estimates. In a companion paper, del Valle et al. [1] demonstrate the usefulness of mathematical simulation for the optimization of extraction time in the supercritical (sc) carbon dioxide (CO_2) extraction of vegetable oil from prepressed oilseed in a 1-m^3 vessel of an industrial multi-vessel SFE plant operating at 40 °C and 30 MPa. The authors used a fully predictive shrinking-core mass transfer model to minimize the operational cost as a function of particle diameter ($0.5 \leq d_p \leq 4$ mm), superficial CO_2 velocity ($2.76 \leq U \leq 11.0$ mm/s), and number (n) of extraction vessels (2, 3, or 4). They observed that the operational cost diminishes as particle diameter decreases, and as the number of extraction vessels increases [1]. However, because of a sharp transition wave that develops when extracting small (≤ 1 mm) particles that separates fully extracted (downstream) from virtually unextracted (upstream) substrate within extraction vessels, del Valle et al. [1] suggested using two-vessel industrial SFE plants for small particles, and three- or four-vessel plants for medium-to-large (≥ 2 mm)

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Nomenclature

Variables and parameter

C_B	annual cost of the extraction batches (USD/year)
C_I	cost of the installed SFE plant
C_L	annual cost of labor (=424,000 USD/year)
C_{PC}	production cost (total) per recovered oil (USD/kg oil)
C_{SC}	annual cost of the solvent cycle (USD/year)
C_{SD}	annual cost of lost CO_2, dissolved in oil (USD/year)
C_T	total annual cost in a SFE plant (USD/year)
d_p	diameter of the diameter (m)
D	diameter of the extraction vessel (m)
E	total amount of vegetable oil produced in a SFE plant in a year (kg oil or ton oil)
I	cost a SFE plant (USD)
I_r	cost of a reference SFE plant having n_r extraction vessels of V_r liters capacity each, and a mass flow rate of CO_2 of Q_r (USD)
L	height of the extraction vessel
L/D	aspect ratio
m	scaling factor for SFE extraction plants (=0.48)
m'	scaling factor for SFE extraction plants reported by Perrut [2] (=0.24)
m_1	scaling factor for the solvent cycle in a SFE plant; parameter in Eq. (7)
m_2	scaling factor for the extraction vessels in a SFE plant; parameter in Eq. (7)
M	mass of the substrate loaded in extraction vessel (kg)
M_{CO2}	mass of CO_2 used in each extraction (kg)
n	number of extraction vessel in a SFE plant
n_r	number of extraction vessel in a reference SFE plant (=2)
N	number of extraction batches in a year
P	pressure of extraction or separation (MPa)
P_n	pressure of design (nominal) of the extraction vessel; 30% above extraction pressure unless otherwise indicated (MPa)
q	specific mass flow rate of CO_2 (kg h^{-1} kg^{-1})
Q	mass or volumetric flow of CO_2 (ton/h or m^3/h)
Q_r	mass flow rate of CO_2 in a reference SFE plant (6000 kg/h of CO_2)
r	annual rate of discount (=6%)
t	time of extraction (h)
t_e	time of extraction process in a extraction vessel (h)
t_r	residence time in an extraction vessel (h)
t_s	time of switch for extraction vessels (h)
T	temperature of extraction or separation (°C)
U	superficial velocity of the CO_2 in the packed bed (m/s)
V_E	volume of the extraction vessels (m^3 or L)
V_r	volume of an extraction vessel in a reference SFE plant (=1000 L)
V_T	total volume or capacity of a SFE plant (m^3 or L)
Y	yield of extraction (%)

Greek letters

α	solvent cycle weighting parameter in Eq. (7)
β	extraction vessels weighting parameter in Eq. (7)
ρ	density of CO_2 (kg/m^3)
ρ_b	bulk density of the bed (=500 kg/m^3)

particles. Finally, del Valle et al. [1] observed that the optimal superficial CO_2 velocity increases as particle diameter decreases so that, within the studied region, best superficial CO_2 velocities are 11.0 mm/s for particles smaller than 1- to 2-mm, 2.76 mm/s for particles larger than 3- to 4-mm, and 5.52 mm/s for particles in between.del Valle et al. [1] estimated an operational cost in a per-batch basis, and excluding the expense of purchasing, installing, and starting-up the industrial SFE plant, which is adequate in the situation where the plant has idle capacity and the plant owner offers toll processing services to third parties. This manuscript expands our previous work to include the capital cost component of the production cost, which is more relevant in situations where informed decisions on investment should be made.

The objective of this second manuscript is to study the production cost of the $scCO_2$ extraction of oil from prepressed oilseeds in industrial multi-vessel SFE plants, including capital costs. The analysis focuses here in unveiling the effect of the number and shape (height-to-diameter, L/D, ratio) of the extraction vessels on the annual cost.

2. Cost of industrial supercritical extraction plants

Based on data collected by Separex over several years, Perrut [2] proposed that the cost of a SF plant for solid substrates is a function of its size defined as the product of the total capacity of the extraction vessels (V_T, in liters), and the capacity of the CO_2 pump (Q, in kilograms of CO_2 per hour), Eq. (1):

$$I \propto (Q \cdot V_T)^{m'} \tag{1}$$

In Eq. (1), m' is a scaling factor that characterizes economies of scale or the reduction in cost when increasing the size of a manufacturing facility; in chemical engineering plant design and economics the most commonly used scaling criteria is the six-tenth rule [3], which is an empirical relationship stating that as the size of a facility increases, its cost increases proportionally less, *e.g.*, as the plant size doubles (100% increase in plant size), its cost increases approximately 52% (estimated using Eq. (1) with $m' = 0.6$). Perrut [2] reported $m' = 0.24$ for plants for the extraction of solids, fractionation of liquids, impregnation of solids, and atomization of particles using supercritical fluids and ranging from laboratory to industrial size.

Using Eq. (1) to estimate plant cost is problematic because of three reasons: (1) it is useless without the cost of a reference plant of known total capacity of extractors and known capacity of CO_2 pump Perrut [2] did not include this information in his manuscript; (2) it suggests that the cost of the plant does not depend on operating pressure, but it should increase steeply as the design pressure increases; and (3) it suggests that the cost of the plant does not depend on the number (n) or shape (L/D ratio) of the extraction vessels, but it should decrease as n decreases, and be less for slim (large L/D ratio) than thick (small L/D ratio) extractors.

To tackle the first problem, the cost of a reference plant can be estimated by referring to reports in the literature or direct quotes from plant manufacturers [4]. To tackle the second problem, all values should be re-estimated for plants with a common pressure rating (P_n, in MPa) by using historical currency exchange rates, Chemical Engineering Plant Cost Index (CECPI) values, and pressure-correction factors to account for variations brought about by differences in currency exchange rate, inflation, and pressure rating, respectively. The CEPCI is an economical index (base value in 1957 = 100), that weights several factors affecting the cost of erecting a process plant in the US including machinery, buildings, installation, and skilled supervision, and that is published monthly in *Chemical Engineering* [5].