Decaffeination of Raw, Green Coffee Beans Using Supercritical CO_2

Background

The worldwide coffee market and the industry that supplies it are among the world's largest. Coffee as a world commodity is second only to oil. Coffee decaffeination is an area in which there has been a notable commercialization of supercritical CO_2 extraction technology. In the past, a methylene chloride extraction process had been used. Methylene chloride is used to extract the caffeine from the coffee beans by continuously circulating the solvent. Typical extraction times range from 24 to 36 hours. Then the solvent must be stripped from the beans by another process that takes from one to eight hours.

The major disadvantage of the methylene chloride process is that it is toxic, and a residue is often left on the beans. Extraction processes that use supercritical CO_2 leave no such residue. Also, supercritical CO_2 is selective exclusively for the caffeine. It does not extract any of the flavor material in the coffee, unlike methylene chloride. Also there is no associated waste treatment of a toxic solvent, and extraction times are generally lower.

Environmental Significance

use of environmentally-friendly solvent

no toxic residues

no associated waste treatment of a toxic solvent

Process Description

The PFD is attached. A cycle begins with the extractor, T-201, being charged with water moistened coffee beans. The extraction is then started by contacting the beans with supercritical CO_2 from the holding tank, TK-202. The CO_2 is passed through the bed of beans for approximately ten hours. After ten hours, 97% of the caffeine has been extracted from the beans. The caffeine-laden CO_2 leaves the extractor and accumulates in the holding tank, TK-201A, until the extraction is finished. Once the extraction is completed, the extractor begins a two-hour down time while it is emptied and charged with fresh beans. Next, the caffeine rich CO_2 in TK-201A begins flowing at a steady rate through the water wash column, T-202. Here the supercritical CO_2 is contacted with a stream of water, which removes 99.5% of the caffeine from the CO_2. The regenerated supercritical CO_2 leaves the water wash in Stream 9. At this point in the process, the CO_2 is at a lower pressure due to pressure drops through the system. Pump P-202A/B makes up for this pressure loss. Next, the regenerated CO_2 begins accumulating in holding tank TK-202. It does so until the two hours of required down time are finished at which point it is fed back to the extractor to begin decaffeinating a new batch of coffee. On this cycle, the supercritical CO_2 exiting the extractor accumulates in TK-201B since TK-201A is still discharging CO_2 from the previous batch.

By alternating between tanks TK-201 A and B, caffeine-rich supercritical CO_2 can feed the water wash column at a steady state. The conditions in the water wash column are the same as those of the extractor to keep the CO_2 in its supercritical state. The caffeine-rich water exiting the water wash is throttled to approximately atmospheric pressure. A small amount of previously dissolved CO_2 is vented from the process vessel V-201 as a gas. Next, process water is added to the caffeine-rich water in process vessel V-202. This makes up for the water lost when the caffeine is concentrated to a 15-wt% solution in the reverse osmosis unit, RO-201. This retentate stream, Stream 7, is then sent to a drying section to obtain solid caffeine. The permeate of the reverse osmosis unit is essentially caffeine free. It is then pumped and sent back to the water wash in Stream 8.

Necessary Information and Simulation Hints

CO_2 becomes a supercritical fluid (SCF) when heated above its critical temperature and compressed or pumped above its critical pressure, which are approximately 31°C and 74 bar, respectively. Most SCF extractions require temperatures and pressures well above the critical temperature and pressure to obtain reasonable recoveries of the extract.

For the process described here, a production rate of 10.8 million kg per year of decaffeinated coffee beans was desired.

The ten-hour extraction time was determined by using a mathematical model for supercritical CO_2 to extract 97% of the caffeine from the coffee beans. The extraction model should account for both the variation of the concentration of caffeine in the CO_2 with time as well as position in the reactor. The model is simplified by modeling the reactor as three well-mixed tanks in series. This is done by dividing the extractor into three well-mixed slices with the outlet concentration of each being a function of the outlet concentration of the previous slice. The model incorporates experimental mass transfer coefficients and partition coefficients for varying temperatures and pressures. The following equations were given as a mathematical model of the extraction of caffeine from raw, green coffee beans in a differential sized extractor[1].

$$\frac{dx}{d\theta} + \frac{x}{\alpha} = -\frac{\phi\left(x - my\right)\left(1 - \alpha\right)}{\alpha} \tag{1}$$

$$\frac{dy}{d\theta} = \frac{\phi\left(x - my\right)}{\left[\beta + \left(1 - \beta\right)K\right]} \tag{2}$$

where

$$x = \frac{C}{C_o}$$

C = caffeine concentration in bed voids

C_o = total caffeine concentration in coffee bean

$$y = \frac{C_i}{C_o}$$

C_i = caffeine concentration in pores of coffee bean

$$\theta = \frac{t}{\tau}$$

t = time

τ = space time

$\phi = K_p \tau$

K_p = combined mass transfer coefficient

m = partition coefficient of caffeine between CO_2 and water

α = void fraction in bed

β = porosity of wet bean

K = equilibrium adsorption coefficient between caffeine bound in bean solid and caffeine in bean pores (assumed to be 1)

Equation (1) is the material balance on caffeine in the bed, and Equation (2) is the material balance on caffeine in the bean.

References

1. Peker, Hulya, M. P. Srinvasan, J. M. Smith, and Ben J. McCoy. "Caffeine Extraction Rates from Coffee Beans with Supercritical Carbon Dioxide," *AIChE Journal*. Vol 38, No. 5, pp. 761-769, May 1992.

Equipment Descriptions

T-201	Extraction Vessel
TK-201 A/B	Caffeine Extract Storage Tanks
T-202	Water Wash Column
V-201	Degasser
V-202	Absorber Feed Tank

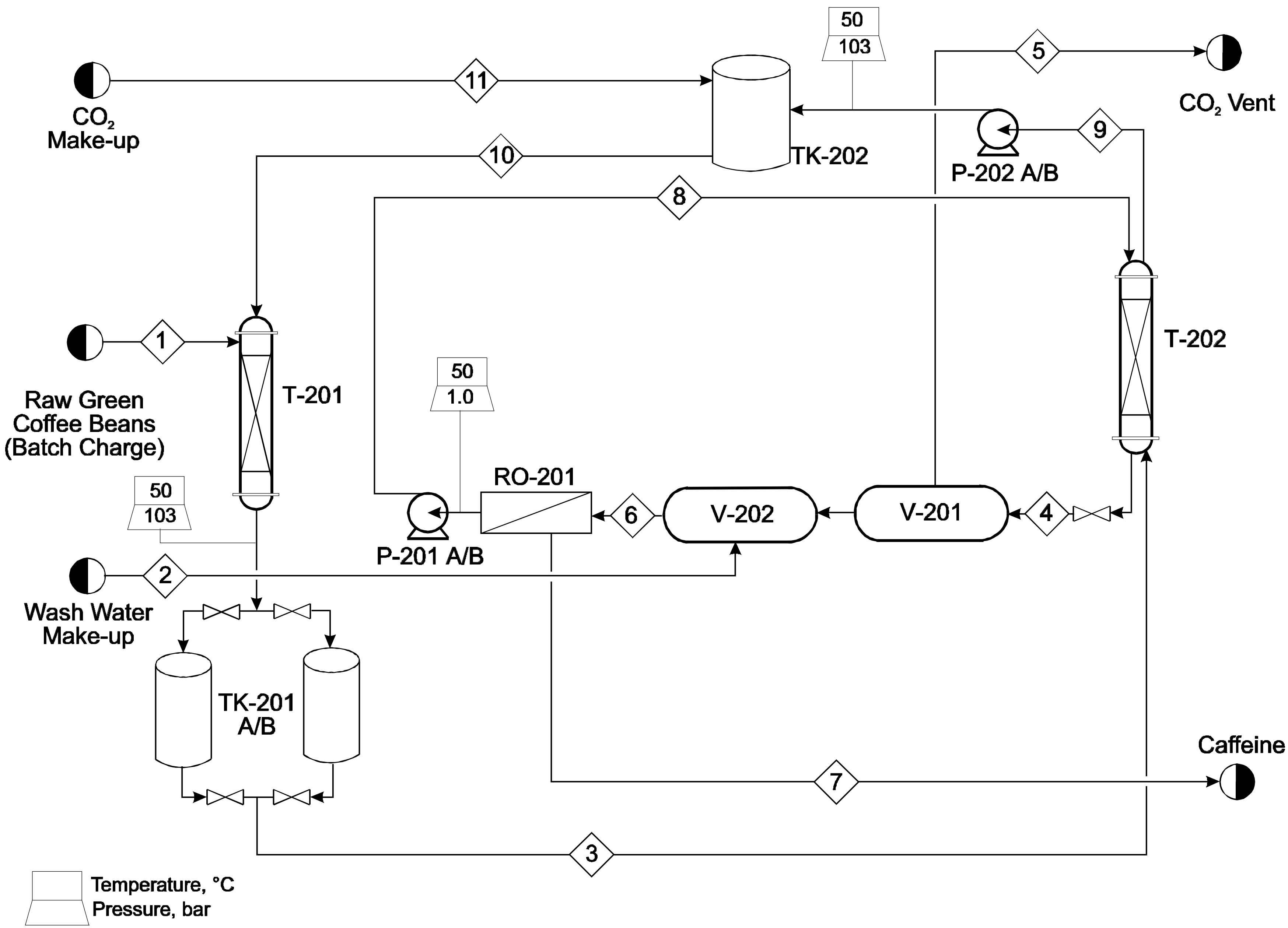
RO-201	Reverse Osmosis Unit
P-201 A/B	Wash Water Recycle Pump
P-202 A/B	CO_2 Recycle Pump
TK-202	CO_2 Storage Tank

Coffee Decaffeination Stream Table

Stream No.	1	2	3	4	5	6
Temperature (°C)	--	50	50	50	50	50
Pressure (bar)	--	103	103	1	1	1
Phase	solid	liquid	SCF**	liquid	vapor	liquid
Total Flow (kg/h)	16130*	88.7	1089	1710	84.4	1714
Component Flowrates (kg/h)						
Carbon Dioxide	--	--	1073	84.4	84.4	--
Caffeine	161.3	--	15.7	15.7	--	15.7
Coffee	16130*	--	--	--	--	1699
Water	--	88.7	--	1610	--	--

Stream No.	7	8	9	10	11
Temperature (°C)	50	50	50	50	50
Pressure (bar)	1	103	98	103	103
Phase	liquid	liquid	SCF**	SCF**	SCF**
Total Flow (kg/h)	104.4	1610	989	1073	84.4
Component Flowrates (kg/h)					
Carbon Dioxide		--	989	1073	84.4
Caffeine	15.7	--	--	--	--
Coffee	--	--	--	--	--
Water	88.7	1610	--	--	--

*The flow of coffee is actually a batch charge at the beginning of each extraction under ambient conditions.
** supercritical fluid



PFD for Extraction of Caffeine from Raw Green Coffee Beans