Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

Theobromine and Caffeine Recovery with Solvent Extraction

Xien Hu[a]; Xuejun Wan[a]; Rongsheng Bal[a]; Huiwen Yang[a]
[a] Institute of Nuclear Energy Technology, Tsinghua University, Beijing, People's Republic of China

Online publication date: 08 November 2003

To cite this Article Hu, Xien , Wan, Xuejun , Bal, Rongsheng and Yang, Huiwen(2003) 'Theobromine and Caffeine Recovery with Solvent Extraction', Separation Science and Technology, 38: 14, 3609 — 3624
To link to this Article: DOI: 10.1081/SS-120023421
URL: http://dx.doi.org/10.1081/SS-120023421

MARCEL DEKKER, INC. • 270 MADISON AVENUE • NEW YORK, NY 10016

SEPARATION SCIENCE AND TECHNOLOGY
Vol. 38, No. 14, pp. 3609–3624, 2003

Theobromine and Caffeine Recovery with Solvent Extraction

Xien Hu,* Xuejun Wan, Rongsheng Bal, and Huiwen Yang

Institute of Nuclear Energy Technology, Tsinghua University, Beijing, People's Republic of China

ABSTRACT

A chloroform extraction process was developed for recovery of theobromine and caffeine from the effluent of a theobromine synthesis plant. The product distributions in the extraction process were studied experimentally. In a chloroform–water system, the caffeine distribution ratio was about 15 and was not affected by pH in the 2 to 12 range, while the distribution ratio of theobromine was about 0.45 for pH < 5 and was strongly affected by the pH of the aqueous phase. The distribution ratio of theobromine was near zero for pH > 10. Therefore, theobromine and caffeine can be recovered separately by adjusting the pH in the aqueous phase. The crude products of theobromine and caffeine can been obtained in the recovery process by evaporation. The thermal stability of theobromine in aqueous solution was also studied. A reciprocating plate column (RPC) is suitable for this extraction process. Pilot tests were

*Correspondence: Xien Hu; Institute of Nuclear Energy Technology, Tsinghua University, Beijing 102201, People's Republic of China; E-mail: huxien@mail.tsinghua.edu.cn.

DOI: 10.1081/SS-120023421 0149-6395 (Print); 1520-5754 (Online)

MARCEL DEKKER, INC. • 270 MADISON AVENUE • NEW YORK, NY 10016

conducted with two columns having 38-mm I.D. Scale-up of the RPCs for an industrial system of 23 t/d capacity was based on the Karr correlation. A 400-mm diameter RPC with a 6-m high cartridge and a pair of 500-mm diameter RPCs with 12-m high cartridges were used for the recovery process. The operating results show that the theobromine recovery was 95% and the caffeine recovery was 99%.

Key Words: Theobromine; Caffeine; Solvent extraction; Recovery.

INTRODUCTION

Theobromine (3,7-dimethylxanthine), caffeine (1,3,7-trimethylxanthine), and theophylline (1,3-dimethylxanthine) are the most important derivatives in commercial pharmaceutical production of N-methylated xanthines. Theobromine, as an isomer of theophylline, is similar to theophylline in therapeutic usage as diuretics, cardiac stimulants, and vasodilators. Theobromine is also used to synthesise Pentoxifylline, which has many potential clinical applications for therapeutic use of cardiovascular diseases and kidney diseases.[1,2] The amount of theobromine extracted from cocoa plants is far below market needs, so theobromine is mainly produced using Traube synthesis. The last step of the synthesis process is that the 3-methylxanthine is methylated at position 7 of the xanthine ring with methyl-sulfate in a basic aqueous solution to form 3, 7-dimethylxanthine, with theobromine then crystallized from the mother solution. Since the selectivity of 3-methylxanthine methylation is hard to control, caffeine is formed as a by-product besides theobromine. Theobromine is a large tonnage product with methylation solutions of about 23 M^3 per day for an 1 t/d yield plant. Both theobromine and caffeine are valuable, but the theobromine value is much higher than that of caffeine. Therefore, theobromine and caffeine should be recovered before the methylation solution is discharged as effluent. The recovery process includes separation of theobromine and caffeine from the methylation solution and then separation of them from each other to obtain crude theobromine and caffeine.

Adsorption separation technology may possibly be used to recover theobromine and caffeine. Although little data for theobromine adsorption were found, caffeine can be adsorpted by many resins for the decaffeination of coffee beans.[3] An adsorption column with the hydrophobic resin, Amberlite XAD-4, was used to remove caffeine from a suspension culture of coffee arabica cells for a caffeine and theobromine production process.[4] Since theobromine and caffeine are both purine alkaloids and have similar properties, both would be adsorpted simultaneously by these resins. So, preparative chromatography technology

should be used to separate the theobromine and caffeine. Preparative chromatography has developed rapidly in recent years, but it is only suitable for low production capacities and continuous operations are difficult. Furthermore, a large amount of solvent is needed for elution in the preparative chromatography process. Such an adsorption process is unsuitable for the recovery of theobromine and caffeine in the effluent.

Supercritical fluid extraction is another candidate for the recovery process. Extraction of caffeine from coffee beans and tea leaves using supercritical carbon dioxide has been comprehensively researched since the 1970s and has been successfully used in commercial decaffeination processes.[5] Recent research has shown that the solubility of caffeine in supercritical carbon dioxide is two orders of magnitude higher than that of theobromine[6] and the extraction process has a higher selectivity for caffeine than theobromine.[7] Li and Hartland found that extraction is difficult with carbon dioxide alone without the addition of a polar cosolvent for extracting the theobromine and other xanthine from the cocoa beans. The results show that the supercritical fluid extraction of theobromine is still a developing technology for industrial applications and in many cases is limited to solid–liquid processes.[8] In general, both the equipment and the operating costs are very high for supercritical carbon dioxide extraction operating at pressures of 80 to 300 bar, and some key problems have to be solved for fractional extraction with countercurrent liquid–liquid contact of the supercritical carbon dioxide with the aqueous effluent.[9]

Conventional liquid–liquid extraction of caffeine with trichlorethylene or chloroform is widely used in commercial decaffeination and caffeine synthesis. Chloroform is of interest as a solvent not only due to the high distribution ratio for the mother solution in caffeine synthesis, but also due to its low boiling point and low cost.[10,11] But solvent extraction of theobromine has not been thoroughly studied and no data is available in the literature, liquid–liquid extraction is attractive because it operates at atmosphere pressure, control is easy, and equipment cost is low. Therefore, it still has potential applications in some fields. The objective of this work was to develop a liquid–liquid extraction process for recovery of theobromine and caffeine that separates both from the effluent.

EXPERIMENTAL

Materials

Standard samples of theobromine and caffeine were produced by the Weibao Pharmaceutical Co. Ltd., China, with purities of 99.0% and 99.9%,

respectively. The original solution used in the pilot tests was the methylation mother solution effluent from the theobromine synthesis process, as supplied by the same company. Organic solvents and other chemicals used in the extraction equilibrium tests were reagent grade. Chloroform used in pilot tests was industrial grade produced by the Beijing Chemicals Corp.

Apparatus

Two RPCs used for the pilot tests were made of glass pipes with flanged connections. The bottom, for settling the heavier phase, was 30 cm in height and 10 cm in diameter. The top section, for segregating the lighter phase, was the same size as the bottom section. The reciprocating plate stack was driven by a variable speed motor and an adjustable yoke. In the test loop, the aqueous phase and the organic phase were pumped by metrical pumps to maintain constant flow rates in each run. The RPC parameters are listed in Table 1.

Procedures

In the extraction phase equilibrium test, the aqueous solution of theobromine and caffeine at fixed concentrations was fully mixed with the organic solvent at different volume ratios. After they reached equilibrium, the theobromine and caffeine concentrations in the aqueous and organic phases

Table 1. Parameters of RPC in pilot tests.

Internal diameter of column	38 mm
Height of internals	5m,[a] 2.3m[b]
Plate diameter	36 mm
Plate thickness	3 mm
Plate spacing	50 mm
Number of plates	98,[a] 45[b]
Diameter of holes	10.8 mm
Arrangement of holes	Equilateral triangle
Triangular pitch	17 mm
Free area	0.366

[a] For theobromine extraction column.
[b] For caffeine extraction column.

were determined using HPLC. The distribution ratio was calculated as the theobromine concentration in the organic phase divided by the theobromine concentration in the aqueous phase at equilibrium. An Agilent Technologies chromatograph was used at the following operation conditions: Agilent Eclipse XDB-C8 4.6 mm ID × 15 cm column, 80/920 (v/v) acetonitrile/ H_2O as mobile phase, 106 bar pressure, 1 mL/min flow rate, 10-L sample, UV detector at 280 nm, and ambient temperature.

In the pilot tests, the column was filled with the aqueous phase and the organic phase, and then sprayed in the inlet located at the top of the column. The mass-transfer test was conducted by measuring the concentration-time relationship of the two phases at the inlet and outlet from start to steady state. The extraction efficiency was calculated from the inlet and outlet theobromine and caffeine concentrations of the aqueous phase at steady state.

In the startup test for the extraction process, the RPC was first filled with theobromine aqueous solution as the continuous phase, then chloroform was fed into the top of the column while the theobromine aqueous solution was fed into the bottom at the setting flow ratio with pulsing. The continuous phase concentration was determined with time by off-line sampling.

RESULTS AND DISCUSSION

Solvent Selection

Caffeine has higher solubility in chlorohydrocarbons, such as chloroform, dichloromethane, and trichlorethylene, so these kinds of solvents are usually used not only in decaffeination liquid–solid extraction processes, but also in liquid–liquid extraction processes. The distribution ratio of caffeine in a water–chloroform system is as high as 18.7 to 22.8 (29°C),[11] so chloroform is successfully used to recover caffeine in industrial processes.[10]

However, as opposed to caffeine extraction, theobromine has low solubility in many ordinary organic solvents and very little data are reported for distribution ratios, so an acceptable organic solvent must be found for an industrial process. In the solvent selection tests, the theobromine distribution ratio between the solvent and the solution in deionized water was determined with a volume ratio of 1:1 at 20°C and pH 6 for various solvents. The concentration of the original theobromine aqueous solution was 404 mg/L. The results are listed in Table 2.

Although the distribution ratios are similar for tributyl phosphate, *n*-butyl alcohol, and chloroform, tributyl phosphate is very expensive for industrial application and *n*-butyl alcohol has a high solubility of 7.8 wt% at 20°C, which

Table 2. Theobromine distribution ratio of several solvents. (O/A = 1, 20 °C, and pH 6–7.)

Tributyl phosphate	0.46
n-Butyl alcohol	0.64
Chloroform	0.48
Ethyl acetate	0.25
Butyl acetate	0.12

would necessitate an expensive recovery system. Although chloroform is volatile and toxic, extraction can be operated under a water seal to reduce the harm from vapors. Also, chloroform has been successfully used as a caffeine extraction solvent in synthetic caffeine plants for many years in China, so chloroform would be acceptable as an extraction solvent in theobromine recovery for industrial applications.

Theobromine Distribution in Chloroform–Water System

The theobromine distribution ratio between chloroform and water was measured for theobromine concentrations from 114 mg/L to 335 mg/L in water at pH 6 and 20°C. The theobromine concentrations in the organic phase are plotted against the concentrations in the aqueous phase in Fig. 1. The mean distribution ratio determined from the slope of the linear relation was 0.45.

Sodium hydroxide and sulfuric acid were used to adjust the pH in the methylation process, so sodium sulfate existed in the effluent. The effect of sodium sulfate on the theobromine extraction was measured for sodium sulfate concentrations of 1% to 5% (wt.) for a theobromine concentration of 529 mg/L in the aqueous phase at pH 6 and 20°C. The result shows that the theobromine distribution ratio in the chloroform–water system increased with increasing sodium sulfate concentration in the aqueous phase as shown in Fig. 2. Sodium sulfate is favored for theobromine extraction with chloroform. The salting-out effect is similar to that for caffeine extraction with chloroform.[10]

The temperature effect on the theobromine distribution was also studied for the chloroform–water system. To consider chloroform with a low boiling point as an extraction solvent, industrial extraction of theobromine and caffeine should operate at environmental temperatures. Therefore, theobromine distribution ratio was measured for 20 to 40°C with no visual change in the distribution ratio.

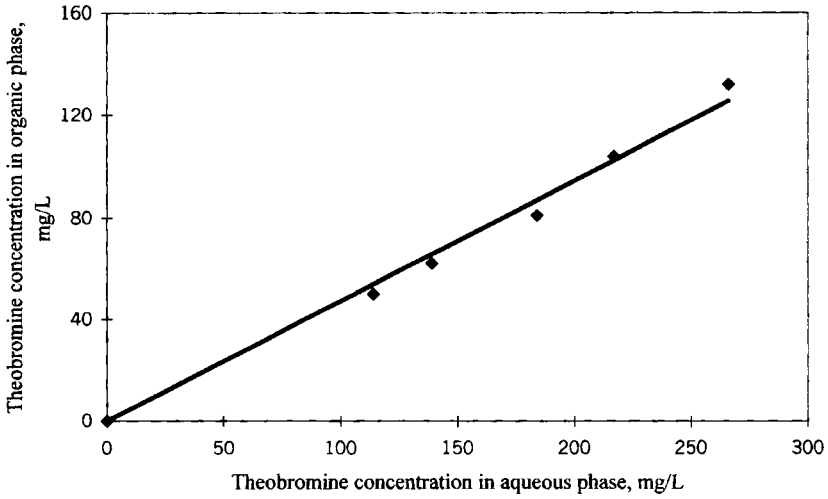

Figure 1. Theobromine distribution ratio in chloroform–water system.

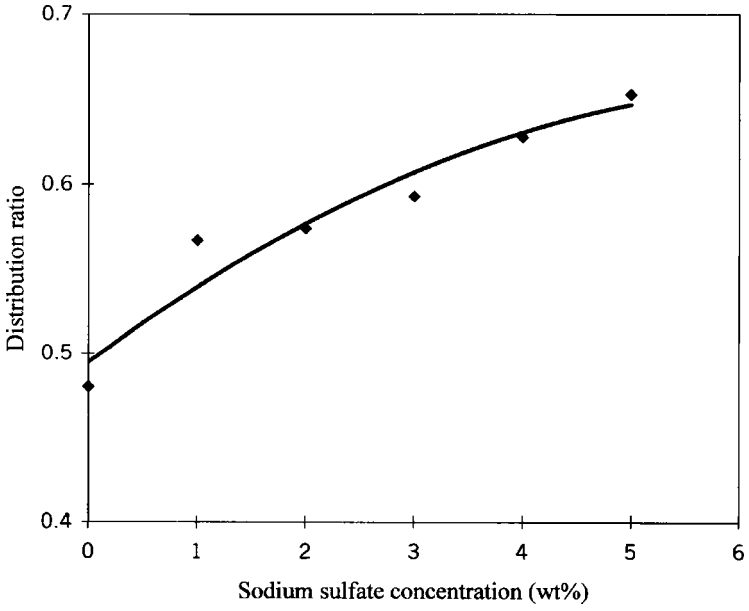

Figure 2. Effect of sodium sulfate concentration in aqueous phase on theobromine distribution ratio.

Effect of pH on Theobromine and Caffeine Distribution Ratios

Theobromine is an isomer of theophylline with an active hydrogen at position 1 of the xanthine main ring, while theophylline has an active hydrogen at position 7 of the xanthine side ring. Since extraction of theophylline is dependent on the pH of the aqueous phase,[12] the extraction of theobromine is probably also affected by the pH in the aqueous phase. Therefore, the effect of the aqueous phase pH on the extraction of theobromine was studied experimentally.

The distribution ratios of theobromine in a chloroform–water system were measured with an initial theobromine concentration of 529 mg/L over a pH range of 1.9 to 12.0. The aqueous phase pH was adjusted with sulfuric acid and sodium hydroxide. The results show that theobromine extraction with chloroform is also strongly dependent on the aqueous phase pH. The distribution ratio of 0.45 was unchanged for pH less than 7, but sharply decreased with increasing pH to near zero for pH higher than 10, as shown in Fig. 3.

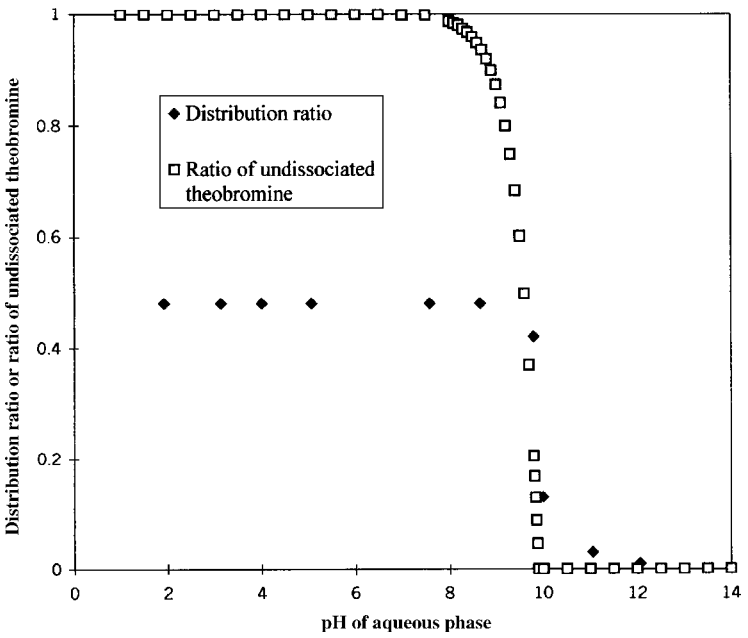

Figure 3. Effect of pH on theobromine distribution ratio. (The ratio of undissociated theobromine is $[HA]/[HA]_0$.)

The theobromine, like theophylline, acts as a very weak acid since the hydrogen at position 1 of the main xanthine ring is dissociable. The dissociation constant, pK_a, of theobromine is 9.9.[1] The ratio of the undissociated theobromine concentration [HA] to the total theobromine concentration $[HA]_0$ in the pH range, calculated using the dissociated constant, is also shown in Fig. 3. The calculated undissociated theobromine ratio is near 1.0 for pH less than 7 and near zero for pH higher than 9.9. The relation between the distribution ratio and the pH is same as the relation between undissociated theobromine ratio and the pH. Therefore, theobromine can only be extracted from the aqueous phase to the organic phase as the undissociated molecule. The theobromine loaded in the organic phase can be transferred into the aqueous phase by stripping with sodium hydroxide solution.

The distribution ratio of caffeine over the range of pH 2 to 12 was also measured in the chloroform–water system. The mean distribution ratio of 18.6 did not change with pH. The distribution ratio was slightly higher than that in a chloroform–water system without the sodium sulfate, since the ratio was enhanced by the sodium sulfate produced during adjusting pH in the tests. Because all the active hydrogens on the heterocyclic ring of xanthine were replaced by three methyl groups, caffeine (1,3,7-trimethylxanthine) will be undissociated in the aqueous phase and cannot give any protons, so the extraction of caffeine will not be affected by the aqueous phase pH. Therefore, theobromine and caffeine may be separated by adjusting the aqueous phase pH.

Thermal Stability of Theobromine in Aqueous Solution

Two methods can be used to regenerate chloroform loaded with theobromine. One method is to strip the loaded organic phase with sodium hydroxide solution, which transfers the theobromine to the aqueous phase, followed by evaporation of the solution to obtain theobromine crystals. Another method is direct evaporation of the chloroform loaded with theobromine. Since evaporation requires elevated temperatures, which may cause decomposition of the theobromine, the thermal stability of theobromine in aqueous solution was examined experimentally. Two 278 mg/L theobromine solutions at pH 5.8 and pH 12.5 were separately heated to 100°C at atmospheric pressure and refluxed for 8 hours. The concentration change with time is shown in Fig. 4. Nine and 7/10 percent Nine and 7/10 percent of the theobromine was lost from the pH 5.8 solution in 8 hours with 9% lost from the pH 12.5 solution in 8 hours. Because of the thermal instability of theobromine in aqueous solution, the second method,

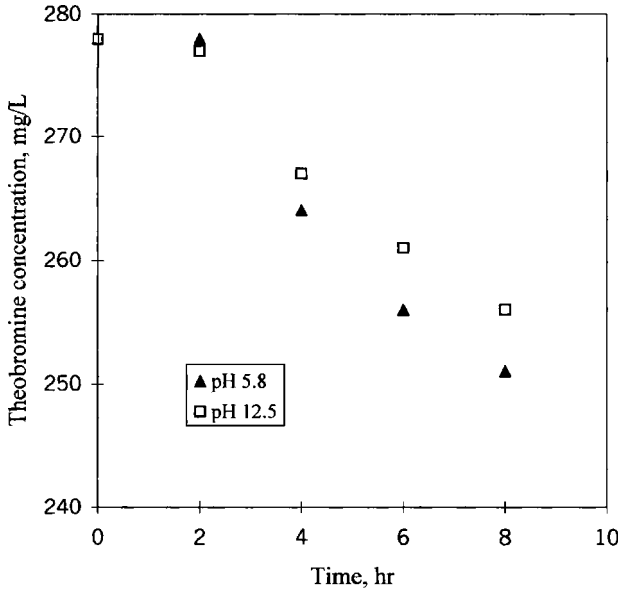

Figure 4. Thermal degradation of theobromine in aqueous solution.

direct evaporation of the loaded organic phase, should be used to separate theobromine and caffeine and to recover the chloroform for recycling into the extraction system. The loaded organic phase will evaporate at 61°C (boiling point of chloroform). No loss of theobromine was visually observed to occur in experiments at this lower temperature.

Separation of Theobromine and Caffeine from the Effluent

In the effluent used for the separation process, theobromine concentration was 2 to 3 g/L, and caffeine concentration was 9 to 10 g/L at pH 8. In addition, the effluent included sodium sulfate and a large amount of undefined organic components. For example, nine undefined components were found using HPLC and those peak areas were 19% of the total peak areas.

Caffeine was recovered from the effluent using crosscurrent equilibrium with chloroform at pH 12.5 and O/A (volume ratio of chloroform to effluent) equal to 0.5. At this pH, the caffeine was extracted into the chloroform while the theobromine remained in the effluent because its distribution ratio is zero.

The effluent was then extracted in the same way with a pH 4.5 and $O/A = 4$ to recover the theobromine. The experimental results show that 99% of the caffeine was recovered in two stages and 95% of the theobromine was recovered in 4 stages (Fig. 5).

The recovery using countercurrent extraction in an industrial application can be estimated from the data for crosscurrent extraction. Since the caffeine has a higher distribution ratio, only three stages will be needed to recover 99% of the caffeine using $O/A = 0.5$. For extraction of theobromine having lower distribution ratio, the flow ratio is also limited by the solubility of theobromine in chloroform. To recover 95% of the theobromine at a flow ratio of 4, five or six stages will be needed for industrial applications.

Recovery Process Design

The experimental results were used to design the recovery process in Fig. 6. The effluent pH was adjusted from 8 to 12.5 with 10 wt% NaOH. The caffeine was extracted with chloroform at $O/A = 0.5$ using four-stage countercurrent extraction to recover 99% of the caffeine. Then, the effluent pH

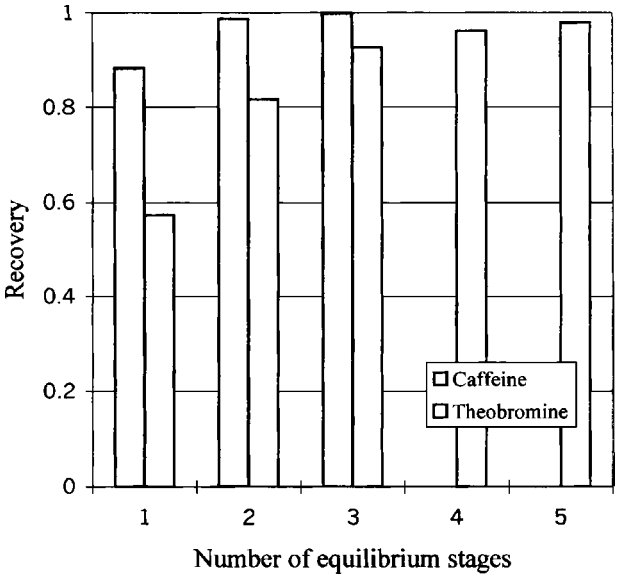

Figure 5. Recovery of theobromine and caffeine with crosscurrent extraction.

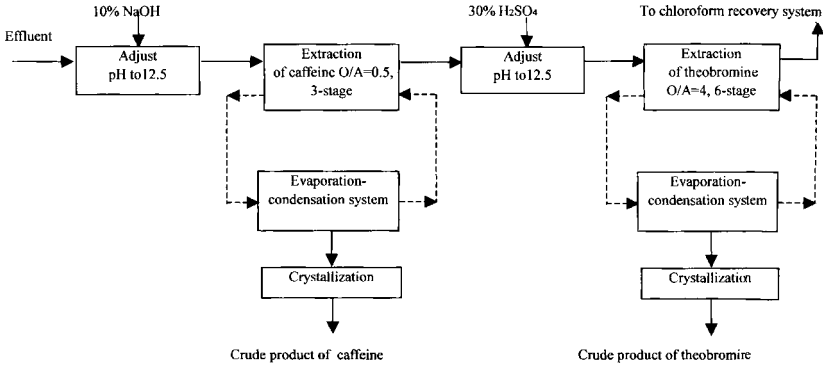

Figure 6. Recovery process of theobromine and caffeine.

was reduced from 12.5 to 4.5 with 30 wt% H_2SO_4. The theobromine was extracted with chloroform at $O/A = 4$ using six-stage countercurrent extraction to recover 95% of the theobromine. The two chloroform streams loaded with caffeine and theobromine were regenerated in separate evaporation systems. The crude caffeine and theobromine products were obtained from the evaporation process. Finally, a kerosene extraction–distillation system was added to recover the residual chloroform in the raffinate from the theobromine extraction to reduce the chloroform loss.[13]

Pilot Tests

The RPC is an efficient extractor for industrial applications that is especially suitable for extraction processes with high throughput and low numbers of stages. The RPC has been successfully used in pharmaceutical extraction processes for many years.[10,12,13] Therefore, the RPC was selected for the industrial extraction of caffeine and theobromine.

The throughput of the chloroform-effluent system in the RPC was evaluated experimentally by measuring the flooding velocity, which was the sum of the superficial velocity of the continuous and dispersed phases. With the effluent as the continuous phase and the chloroform as the dispersed phase, the flooding velocity was 0.83 cm/s for a 3.3-Hz pulsation frequency, 13-mm amplitude, and a flow ratio (O/A) of 4. For a flow ratio (O/A) of 0.5, 4.3-Hz frequency, and the same amplitude, the flooding velocity increased to 1.85 cm/s. The flow ratio was found to significantly affect the flooding velocity.[14]

Table 3. RPC mass transfer for extraction of caffeine and theobromine in pilot tests.

Composition of mass transfer	Frequency (Hz)	Amplitude (mm)	Flow ratio	Recovery	HETS (m)
Caffeine	5.0	13	0.5	0.999	1.00
Theobromine[a]	3.9	13	3.8	0.975	0.93
Theobromine[b]	4.2	13	4.0	0.965	1.14

[a] For theobromine–chloroform–water system.
[b] For theobromine–chloroform–original effluent system.

The experimental results of mass transfer are listed in Table 3, which shows that the HETS (height equivalent for a theoretical stage) value were 1.00 m and 1.14 m for caffeine and theobromine extraction, respectively.

The startup process for theobromine extraction in a chloroform–water system was also investigated experimentally. The results show that the continuous phase concentration at the outlet decreased with time to an equilibrium concentration and that the startup process required about 250 minutes to reach stable operation for the given operation conditions (Fig. 7).

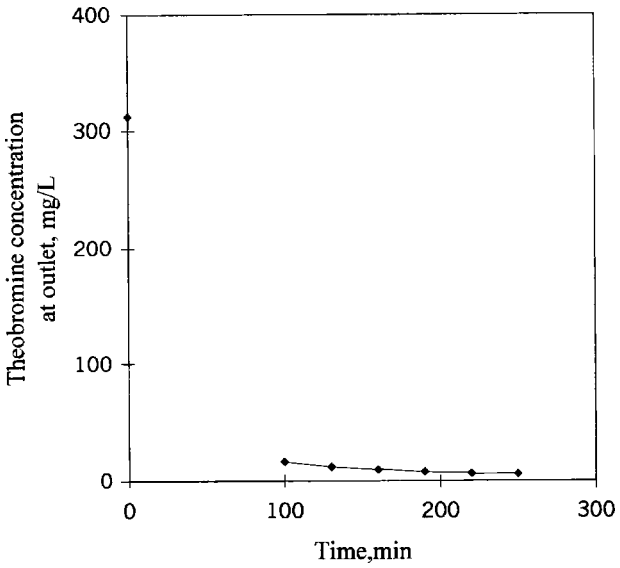

Figure 7. RPC starting process in pilot tests for theobromine–chloroform–water system.

Table 4. Specifications of theobromine and caffeine recovery system.

Capacity	23 t/d
Recovery (%)	
Caffeine	99
Theobromine	95
Purity of recovered crude products (%)	
Caffeine	>80
Theobromine	>70

Scale-up Design and Commercial Application

A system to recover caffeine and theobromine from the effluent was designed with the specifications listed in Table 4.

The scale-up design of the RPC followed the Karr correlation.[14] In the scale-up design, the throughput per unit cross section should be the same as that of the pilot column and HETS should be equal to the ratio of the scaled-up column diameter to the pilot column diameter to the 0.38 power. Therefore, a 400-mm diameter RPC with a 6-mm height cartridge was used for the caffeine extraction. A pair of 500-mm diameter RPCs with 12-m height cartridges were used side by side for the theobromine extraction to allow operating flexibility.

The recovery system has been operating successfully for 1 year and has met the expected design specifications. The caffeine purity in the crude product recovered from the effluent was 94% and that of theobromine was 97%, both greater than the specified purity. The results show that chloroform provides good selectivity to separate theobromine and caffeine from other organic components. The operating experience also shows the RPC throughput has operating flexibility for expanding capacity.

CONCLUSION

Theobromine and caffeine in the effluent of a theobromine synthesis plant was recovered with a solvent extraction process using chloroform as the solvent. The caffeine distribution ratio in the chloroform–water system was about 15 and was not affected by pH over the 2 to 13 range. The theobromine distribution ratio in the chloroform–water system was about 0.45 for pH less than 5 and was strongly affected by aqueous phase pH, with the theobromine distribution ratio near zero for pH higher than 10. Therefore, theobromine and caffeine can be separately recovered by adjusting the aqueous phase pH.

The experimental results were used to design a recovery process. Caffeine was first extracted at pH 12.5 with chloroform, then, the effluent pH was reduced from 12.5 to 4.5 to extract the theobromine with chloroform. The chloroform streams loaded with caffeine and theobromine were separately regenerated by evaporation to obtain their crude products.

RPCs were successfully used to treat the effluent. Pilot tests were conducted with 2.3-m internal height and 5-m internal height columns with 38-mm I.D. The pilot test data were then used to design RPCs for industrial applications using the Karr correlation. A 400-mm diameter RPC with a 6-m height cartridge and a pair of 500-mm diameter RPCs with 12-m cartridges were used for the recovery process. The recovery system capacity was 23 t/d. The operating results show that the theobromine recovery was 95% and the caffeine recovery was 99%.

REFERENCES

1. Lister, J.H. *The Chemistry of Heterocyclic Compounds*; Wiley: New York, 1996; Vol. 54, 254.
2. Shen, F.; Yuan, W.; Zhang, G. Clinical applications of pentoxifylline for kidney diseases. Chin. J. New Drugs Clin. Remark **2001**, *20* (2), 146–148, (in Chinese).
3. Qian, T.; Liu, W.; Li, L. *Adsorption Resin and Its Applications*; Chem. Ind. Press: Beijing, 1990; 617 pp, (in Chinese).
4. Kurata, H.; Kawai, A.; Seki, M.; Furusaki, S. Increased alkaloid production in a suspension culture of coffea aarabica cells using an adsorption column for product removal. J. Ferment. Bioeng. **1994**, *78* (1), 117–119.
5. McHugh, M.; Krukonis, V. *Supercritical Fluid Extraction, Principles and Practice*, 2nd Ed.; Butterworth-Heinemann, 1994; Boston, 4 pp.
6. Johannsen, M.; Brunner, G. Solubilities of the xanthines caffeine, theophlline and thoebromine in supercritical carbon dioxide. Fluid Phase Equilibria **1994**, *95*, 215–226.
7. Saldana, M.D.A.; Mohamed, R.S.; Mazzafera, P. Supercritical carbon dioxide extraction of methylxanthines from mate tea leaves. Braz. J. Chem. Eng. **2000**, *17* (3), 251–259.
8. Li, S.; Hartland, S. New industrial process for extracting cocoa butter and xanthine with supercritical carbon dioxide. J. Am. Oil Chem. Soc. **1996**, *73* (4), 423–429.

9. Wang, T. Supercritical fluid extraction. In *Handbook of Solvent Extraction*; Wang, J., Chen, G., Eds.; Chem. Ind. Press: Beijing, 2001; 1020–1022, (in Chinese).
10. Hu, X.; Dai, W.; Wang, X.; Guo, Z.; Liao, B.; Bai, R. Study of extraction process of caffeine by chloroform. J. Tsinghua Univ. (Sci. Technol.) **1995**, *35* (3), 13–19, (in Chinese).
11. Hamm, W. Liquid–Liquid extraction in food processing. In *Science and Practice of Liquid–Liquid Extraction*; Thorton, J.D., Ed.; Clarendon Press: Oxford, 1992; Vol. 2, 334–337.
12. Hu, X. Recovery of theophylline in effluent with 2-ethylhexanol extraction process. Sep. Sci. Technol. **1999**, *34* (14), 2905–2922.
13. Hu, X. Recovery of chloroform from effluent with solvent-distillation process. Sep. Sci. Technol. **1997**, *32* (12), 2039–2050.
14. Lo, T.C.; Baird, M.H.I.; Rama, R.N.V. The reciprocating plate column-development and applications. Chem. Eng. Commun. **1992**, *116* (67), 66–88.

Received May 2002
Revised February 2003