บทความวิจัย

Mass Transfer of a Small-Medium Enterprise (SME) Size Pineapple Juice Extractor

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Abstract

The compact reversing counter current extractor (RCCE) for pineapple juice from its peel was designed and developed. Consequently, the extraction trail with the RCCE were studied using different three variables, namely draft, retention time and extraction temperature. The equilibrium distribution and diffusion coefficients of solute in solid phase in the batch extractor were estimated. The results show that at draft value of 2, retention time of 90 min and extraction temperature of 70°C provided a maximum percentage yield of 70.9. In the steady state, a solute concentration profile in solid and liquid phases at any point throughout this extractor had the same pattern as the other states. In addition, the mathematical diffusion-back-mixing model was simulated to describe kinetic of mass transfer in various conditions. The simulated data by diffusion-back-mixing model had good agreement with the experimental data in the solid phase whilst the simulated data showed the same trend as the experimental data in the liquid phase. The results showed that the back-mixing process caused increasing of mass transfer of solutes on the solid surface area. This is corresponded to the reduction in driving force due to its resistance to mass transfer. The differences between experimental and predicted results are highly related to the variation of Biot number and Peclet number.

Introduction

Pineapple *(Ananas cosmosus)* is consumed either fresh or in the processed forms such as pineapple juice, pineapple piece in syrup etc. In Thailand, pineapples normally plant in the eastern and the southern part and the pineapple industrial factories are the medium and large enterprise sizes which are capable of 20-50 ton of raw material/day and over 50 ton of raw material daily, respectively. So, Thailand is one of the main exporters of pineapple products and pineapple juice concentrate is also exported and take in some million dollars annually (Thailand Foreign Agricultural Trade Statistics 2004, 2005). To be competitive, it becomes more critical to improve the efficiency of the whole process to reduce specific energy consumption and minimize the environmental problems.

Pineapple juice extraction is commonly operated by mechanical expression. This method produces yield percentage of 60-70% as compared to yield percentage of 80-90% obtained from the diffusion process followed by mechanical extrusion. It found that a few big processing plants have invested in the diffusion process, even if it has high efficient method. This may be because expense for development of a new plant is quite high. Thus, the potential of juice concentrate production from pineapple waste is still highly unexplored. Apparently, no serious investigation has been carried out to trap this potential. The pilot scaled extractor, which was based on Casimir (1983), was chosen because of its simplicity and efficiency (Casimir, 1983; Bioquip, 1984; Gunasekaran *et al*., 1989). Some previous research also reported juice extraction processes from apples and pears using the RCCE unit. Various diffusion models were simulated for predicting juice extraction mechanism. However, a low back-mixing process (high Peclet number) using the RCCE unit in the previous research (Gunasekaran, 1989) showed that the simulated results were not related to those of experimental results.

One of the most comprehensive and fundamental model using diffusion and back-mixing theory was developed by Lee and Schwartzberg (1990). The solution of counter-current diffusion model (CCE) with an extent of back-mixing in liquid phase was carried out. However, this solution was rather complex and might have a minor discrepancy because, for the asymptotic case (plug-flow model), the solution did not match with the well-known solution (Tirawanichakul *et al.*, 1996) given by Spanink (1983).This realized that the solution of any mathematical models were of specific form and depended on the raw material. Consequently, a few understanding in mass transfer in juice extraction process for pineapple peels in a small-medium enterprise size extractor in Thailand was researched.

So, the objectives of this work are to investigate the potential of RCCE in the extraction of pineapple juice from its peels for a small-medium enterprise size extractor and finally, to develop mathematical model for studying of mechanism for the mass transport phenomena using some fundamental parameters as follows: an effective diffusivity, draft value and the delay time of plasmolysis.

Model Development

In practice, a linear velocity of liquid phase in RCCE or other kind of CCE can vary greatly along the trough due to its slope and the movement of both phases relative to the screw. However, the volumetric flow rate of solid and liquid phase along the trough may be assumed constant at steady state conditions. For this reason, our development here will be based on volumetric flow rate of solid and liquid phases in stead of their average linear velocities. This is not a normal practice used in traditional back-mixing theory. Nevertheless, it can be shown that the following model will give an equivalent result as given by the conventional extractor in case of the constant average velocity.

To consider a mass balances on a CCE, the schematic diagram can be shown in Fig.1. The following assumptions are formulated as :

1) The volumetric flow rate of both solid and liquid phase is constant.
2) The mass transfer coefficient (K_x), draft (α) and equilibrium distribution coefficient (m) are constant along the extractor and
3) The volumetric dispersion coefficient (D_x and D_y) are constant and are independent of position along the trough.

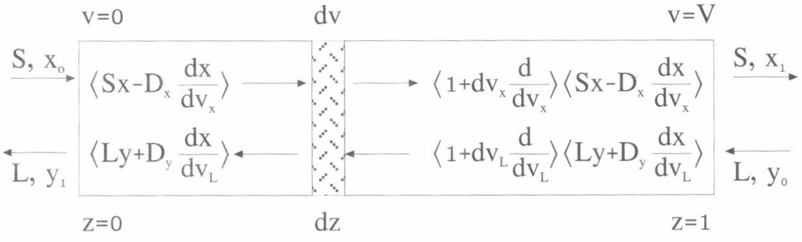

Fig.1 Material balance of the RCCE system

The following equations explaining mass balance between solid phase and liquid phase in the extractor can be written as:

For solid phase,

$$\left\langle \frac{dx}{dz} - \frac{1}{P}\frac{d^2x}{dz^2} \right\rangle + T'(x-x^*) = 0 \qquad (1)$$

where P is defined as follows :

$$P = \frac{sv_x}{D_x},\ T' = \frac{K_xV_x}{S} = K_xt_f \qquad (2)$$

For liquid phase,

$$\left\langle \frac{dy}{dz} + \frac{1}{R}\frac{d^2y}{dz^2} \right\rangle + T''(y-y^*) = 0 \qquad (3)$$

where R is also defined as follows :

$$R = \frac{LV_L}{D_y},\ T'' = \frac{K_xV_L}{L} = K_xt_f \qquad (4)$$

where

D_x, D_y	volumetric dispersion coefficient in solid and liquid phase, respectively, m^6/s
K	overall mass transfer coefficient, respectively, s^{-1}
L	volumetric flow rate of liquid phase, m^3/s
P	Peclet number of solid phase, m^3/s
R	Peclet number of liquid phase, m^3/s
S	volumetric flow rate of solid phase, m^3/s
T', T''	dimensionless extraction time at solid and liquid phase, respectively
t	the actual extraction time, s
t_t and t_p	time lead due to initial solute distribution in solid and time delayed due to plasmolysis, respectively
t_f	the theoretical extraction time, $t_f = t+t_t-t_p$
V_x, V_y or V_L	total volume of solid and liquid phase, respectively, m^3
x	average solute concentration in solid at time t or at position z, kg/m^3
x*	average solute concentration in solid at steady state, kg/m^3
y	average solute concentration in liquid at time t or at position z, kg/m^3
y*	average solute concentration in liquid at steady state, kg/m^3
Y	solute concentration in liquid at time t or at position z
z	dimensionless length

subscript x and y mean solid and liquid phase, respectively.

To get the solution of Eqs. (1) and (3), the boundary conditions are shown as follows:

$$\text{at } z = 0; \quad \bar{x}_{in} = \bar{x} - \frac{1}{P}\frac{d\bar{x}}{dz} \qquad (5)$$

$$\text{at } z = 1; \quad y_{in} = y + \frac{1}{R}\frac{dy}{dz} \qquad (6)$$

$$\text{at } z = 1; \quad \bar{x}_{out} = \bar{x},\ \frac{1}{P}\frac{d\bar{x}}{dz} = 0 \qquad (7)$$

$$\text{at } z = 0; \quad y_{out} = y,\ \frac{1}{R}\frac{dy}{dz} = 0 \qquad (8)$$

where

$\bar{x}$, $\bar{y}$	average solute concentration in solid and liquid phase

subscript in and out means inlet and outlet, respectively.

Assumption of this extraction process is that the backing in solid phase is negligible and the flow pattern in solid phase is in form of plug-flow (P and R → infinite value) whilst in liquid phase, it is in backing current flow. By analogy, the general solution of an ordinary differential equation for the conventional back-mixing formulation is the same as that given by Mechlenbergh and Hartland (1975).

In case of extraction constant does not equal to 1 ($J \neq 1$), then, let J equals to $1/\alpha$ or equals to q/m when m is a distribution coefficient.

$$\frac{x_0 - x}{x_0 - y_0/m} = \frac{(1-w_1)^{\frac{H_1}{q_1}} - (1-w_2)^{\frac{H_2}{q_2}}}{(1-JW_1)^{\frac{H_1}{q_1}} - (1-JW_2)^{\frac{H_2}{q_2}}} \qquad (9)$$

$$\left\langle \frac{y - y_0}{mx_0 - y_0} \right\rangle \alpha = \frac{(w_1 - H_1W_1)/q_1 - (w_1 - H_2W_2)/q_2}{(1-JW_1)^{\frac{H_1}{q_1}} - (1-JW_2)^{\frac{H_2}{q_2}}} \qquad (10)$$

where q_1 and q_2 are the roots of equations of the first and second Eigen value, respectively

$$q^2 + q(T' + R) = \frac{T'R(1-\alpha)}{\alpha} \qquad (11)$$

$$H_1 = 1 + \frac{q_1}{R}, \; w_1 = \exp(q_1 z), \; w_2 = \exp(q_2 z) \qquad (12)$$

$$W_1 = \exp(q_1) \quad \text{and} \quad w_2 = \exp(q_2) \qquad (13)$$

where

Bi	Biot number = kml/D_S
k	film or surface mass transfer coefficient
l	characteristic length, m
D_s	Diffusion coefficient in solid phase, m^2/s
y	average value of input solute concentration in liquid at entrance, kg/m^3
W_1, W_2	weight of pineapple peel before and after extraction, g
α	Draft value, dimensionless

When K_x, R, Bi and time lead was determined and let them put in Eqs.(9) and (10), the predicted value of solute concentration in solid and liquid phase along the extractor length can also be calculated.

Experimental Procedures

1. Material and methods

1.1 Extractor unit

The extractor design modified similarly to that used in CSIRO and the University of Delaware as shown in Figure 2. The extraction unit was composed of a U-extruder with a length of 2.20 m., width of 0.218 m and height of 0.30 m, an electrical heating unit of 1.3 x 3 kW.

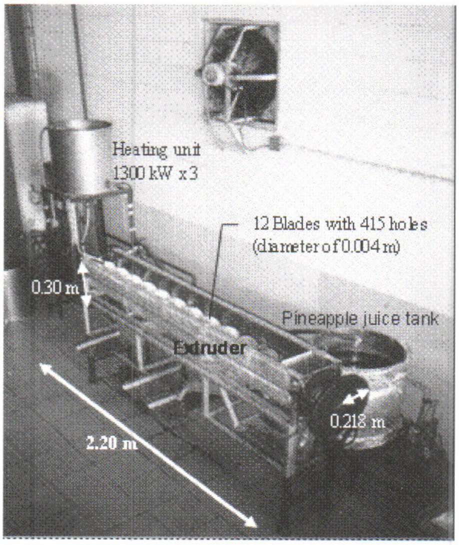

Figure 2 Illustration of the SME size pineapple juice extractor

In this investigation, the experimental set-up conditions were listed as follows,

a) In all trials, forward and reverse rotational speeds of the screw were identical. However, in each cycle, the screw moved in forward and reverse direction for 25 and 22 s, respectively, 1 percentage progression value of 6.38.

b) In all experimental trials, the trough slope was fixed at 5 degrees.

c) Before extraction, the pineapple peel with non-uniform shape was stream in 5 min. at 70°C for 5 min.

d) The solid feed rate was set-up at 12 kg/h and manual feed rate of raw material (pineapple peel) was about 2 kg per each 5 minutes. During this period, the raw material was heated from 30°C to about 55.0, 62.5 and 70°C and the cell structure was plasmolyzed (so that t_p was essentially zero).

e) The average extraction temperature was controlled at 55.0, 62.5 and 70°C.

f) Retention times of solid were set as 50, 70 and 90 min.

g) The ratios of liquid rate to solid feed rate were 1.0:1.0, 1.5:1.0 and 2.0:1.0. Drafts were calculated by averaging the liquid to solid ratio at entering and leaving ends.

h) Then, an equilibrium distribution constant was 1.14 for all experiments.

It realizes that thermal treatment for agro-product with a high temperature is commonly applied to maintain quality and extend shelf life. However, this treatment also affects the quality of product for example, browning reaction, increase of free fatty acid, vitamin C reducing etc (Fontana *et al.*, 1993; Barreiro *et al.*, 1997; Avila *et al.*, 1999; Tirawanichakul *et al.*, 2003; Tirawanichakul *et al.*, 2004; Marisa *et al.*, 2005). Marisa *et al.* (2005) studied the effect of thermal processing on the quality of pineapple juice. Three indexes, namely colorimetric in *Hunter* unit, hydroxymethylfurfural (HMF) and brown pigment formation, were used for determining the quality loss of product at heat treatment with temperature ranging from 55 to 95°C. They concluded that dependence of the rate constant on temperature could be represented by Arrhenius equation whilst HMF and brown pigment formation increase 4.8d linearly with heating time. Thus, the extraction temperature in this work was fixed at 55.0, 62.5 and 70°C for maintaining quality of pineapple juice.

1.2 Methods

During experiments following the conditions in section 1.1, the extractor was axially divided to 6 parts and the samples (pineapple peel and juice) were taken from them. Figure 3 showed the experimental set-up and tested position. In solid phase, peels were picked up at position no.1-7 whilst pineapple juice was taken at position no.1-6. K-typed thermocouple used for measuring the temperature inside extractor was connected with a data logger with an accuracy of ± 1°C.

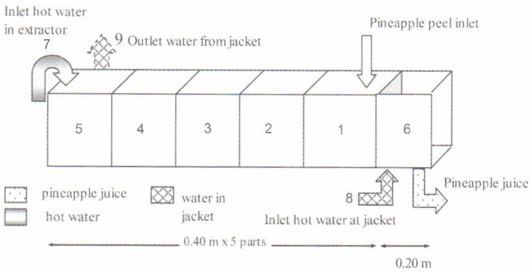

Figure 3. Schematic diagram of SME size extractor and sampling point

2. Parameter estimation

2.1 *Solute diffusivity and time delayed due to plasmolysis*

Batch extractions with various conditions were carried out and the extraction curves and solid dimension were used for calculating the diffusivities, following by the previous work (Siripatana, 1986).

2.2 *Overall mass transfer coefficient*

The overall mass transfer coefficient (K_x) was defined by the following basic equation below:

$$-\frac{d\bar{x}}{dt} = K_x\left(\bar{x}-\frac{y}{m}\right) \qquad (14)$$

where K_x was evaluated directly from the actual concentration profiles.

That is firstly, the concentration profiles were fitted to be the 5th order polynomial function with constant parameters. Then the average K_x values were searched by comparing them with the solution of Eq.(14) such that the sum square of error was minimized.

2.3 *Peclet number in liquid phase.*

In liquid phase, Peclet numbers (R) were not determined directly from concentration profile. Rather, they were treated as parameters of back-mixing model (Eqs. 1-14) which must be determined by non-linear fitting.

2.4 *Solid characteristic dimensions.*

The fresh pineapple peel provided by Thai Pineapple factory, Prachupkhirikhan Thailand resembled in form of a small rectangular blocks with dimension of 0.52 x 4.90 x 5.20 cm^3. Assumption is that the diffusion of mass transfer throughout the external surface was negligible since the surface (skin) of the pineapple fruits is much less permeable to solute than the inner part as shown in Figure 4.

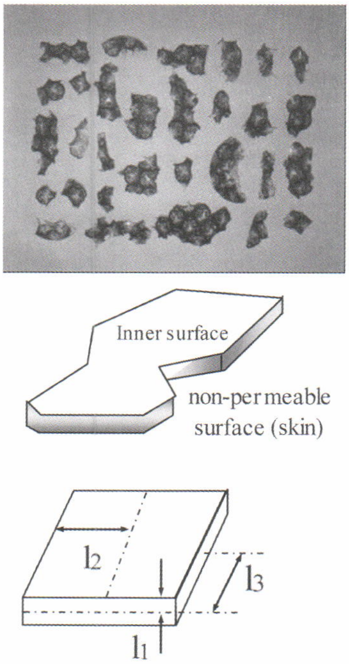

Figure 4 Illustration of pineapple peel samples for extraction and characteristic dimensions

2.5 Biot number

By following this approach, with some modification for rectangular shape (l_1, l_2, l_3), the approximate equation can be obtained as follows,

$$Bi = \left[\frac{p}{\frac{1}{g(\alpha, Bi)} - 1}\right]^{1/k}$$

$$g(\alpha, Bi) = \frac{Sh}{2h(\alpha, \eta)}, \qquad (15)$$

$$sh = 2\frac{K_x}{D}\left(\frac{1}{l_1^2 + l_2^2 + l_3^2}\right)^{-1}$$

$$h(\alpha, \eta) = 2.460 + 0.4321\eta + \frac{0.528 + 0.5435\eta}{\alpha} + \frac{0.03909 + 0.08694\eta}{\alpha^2} \qquad (16)$$

$$p = 2.1426 + \frac{0.9314}{\alpha} + \left(0.1575 + \frac{0.9786}{\alpha}\right) \qquad (17)$$

$$k = 2.1426 + 0.01467\eta \qquad (18)$$

2.6 Time lead due to initial solute distribution in solid

Such a using the concept idea of the previous works (Siripatana, 1986; Tirawanichakul *et al.*, 1996), the following approximate relation between time lead and volumetric dispersion coefficient in solid phase can be derived.

$$t_f = -\frac{\ln C_1^3}{q_1^2 D_x\left(\frac{1}{l_1^2 + l_2^2 + l_3^2}\right)} \qquad (19)$$

where $C_1 = -\frac{2\alpha}{2.466\alpha - 0.525}$

Here, q_1 is the first root of $\tan q_1/q_1 = \alpha$

Results and discussion

1. Solute diffusivity and plasmolysis period

The results from batch extraction trials showed that, in the temperature of 50.0, 62.5 and 70°C, the solute diffusivity and time of plasmolysis were linearly and exponentially related to extraction temperature, respectively. These results can be formulated as follows,

$$D_x = 1.347\text{x}10^{-10}T_{abs} - 3.912\text{x}10^{-8} \qquad (20)$$

$$t_p = 2664 \exp(-0.115T) \qquad (21)$$

Where T = extraction temperature, °C
Subscript abs means absolute temperature

Eq.(20) indicates that the diffusion coefficient of solid phase has a linear relation to the absolute operating temperature. This is due to the fact that fiber of the pineapple peel has more sensitivity to the thermal stress under high temperature.

This diffusivity of soluble solids, which is mainly sucrose, are one order of magnitude higher than that of sucrose in aqueous solution (0.62×10^{-9} m^2/s at 70°C). This indicates that, although the asymptotic extraction curves follow exponential pattern as predicted by diffusion theory, the main driving force of solute transfer was by different mean the main mechanism of the solute transfer. This requires more in-depth investigation. However, here it is sufficient to say that the values of diffusivity observed here is 10 times higher than of molecular diffusion. These results are in good agreement with those given by Beristain *et al.* (1990) and Sodchit (1993).

In temperature range of 50.0, 62.5 and 70.0°C, t_p approached zero exponentially as extraction temperature. This is because at high steaming temperature before re-extraction process, breakdown tissue occurred. This trend corresponds to the previous work which were studied the diffusion of solute from pears and apples and for solute infusion into pineapple slices (Gunasekaran *et al.* 1989).

2. Overall mass transfer coefficient (K)

It was found that the overall mass transfer coefficients varied from 3.80×10^{-4} to 9.99×10^{-4} s^{-1}. It should be emphasized that in fact the real cause of difference in K value was the screw action not the total extraction time. Thus, in stead of reducing the total extraction time in order to increase K_x the extractor trough can be lengthened. This has an advantage of increasing K_x, without getting side effect from lower residence time (which in turn lower yield).

3. Biot number

Biot number characterizes the ratio of in-solid mass transport resistance to resistance at the solid-liquid interfaces. Then Eq.(14) can be written as follows:

$$K_x = \frac{Sh\ D}{2}\left(\frac{1}{l_1^2 + l_2^2 + l_3^2}\right) \qquad (22)$$

and $Sh = 2g(\alpha, Bi)\ h\ (\alpha, \eta)$

$$g(\alpha(Bi)) = \left(1 + \frac{P}{Bi^k}\right)^{-1} \qquad (23)$$

It is realized that the effect of total extraction time and temperature on K_x is similar to that on Bi value because, as shown in the Eqs. (22)-(23), if α and D are constant, a K_x value will change in the same direction as that obtained of Bi value.

4. Peclet number

It was confirmed that, for the raw material used in this work the back-mixing in solid phase was of minor importance factor. In contrary, the back-mixing in liquid phase was quite considerable and the values are in the range of 1.5 to 3.5.

According to the experimental data, most of factors are insignificantly related to the Peclet number except the draft value. The effect of draft had a certain trend, although the variation was a quite large and a following formula can be written as below :

$$R = 4.12 - 1.04\alpha \qquad (24)$$

If one notices that, by the relationship between R, L, V_L and D_y (defined as R equals to LV_L/D_y), one expects that, if the volumetric dispersion coefficient in liquid phase (D_y) is constant, increasing of the α value (in effect increasing L) will be proportional to increase R value. This evidence is exactly opposite of the experimental work. Thus, as α increases, D_y increases due to the stronger back-mixing. On the other hand, this is because of the high efficient back-mixing.

5. Effect of operating condition on extraction yield

The effect of draft value ranging of 1.0-2.0, three different extraction temperatures of 55.0, 62.5 and 70.0 °C and operating time of 50-70 min on percentage yield were studied. The results show that percentage yield increases proportionally with an increase in the draft value. The percentage yield varies from 58.5 to 72.3 whilst the extraction temperature of 70.0°C is the most suitable value for this machine comparing to those results of 55.0 and 62.5°C, respectively. Table 1 illustrates the increasing of percentage yield difference at various experimental conditions. The results showed that an average increasing of percentage yield difference under the condition of extraction time steps from 50 to 70 min. and from 70 to 90 min. was 1.97 and 1.81, respectively. From Column nos.3 and 4 as illustrated in Table 1, increasing step of extraction time from 50-70 min. to 70-90 min. has insignificant effect on increasing of percentage yield. In addition, extraction with operating time over 90 min. has a little increasing of percentage yield. This may be because there are 2 main factors affecting to yield as the draft value and extraction temperature.

Table 2 shows the percentage yield difference with two temperature ranges of 55.0-62.5°C and of 62.5-70.0°C under various operating conditions. The experimental results show that an average increasing of percentage yield difference under the condition of extraction temperature from 55.0-62.5°C and from 62.5-70.0°C was 0.68 and 3.30, respectively. This corresponds to results from the previous section.

At the low retention time of 50 min., there was a significant affects on percentage yield. These imply that a low extraction temperature of 55.0°C and a low operation time of 50 min. are not the suitable conditions for producing a high yield of

Table 1. Increasing of percentage yield difference under various operating conditions of a pineapple juice extractor at three extraction temperatures.

Extraction temperature (°C)	Draft value	Percentage difference of yield at two ranges of extraction time (%)	
		50-70 min.	70-90 min.
55.0	1.0	3.91	2.83
	1.5	2.01	3.89
	2.0	4.01	3.74
62.5	1.0	1.52	1.11
	1.5	1.48	2.87
	2.0	3.18	1.52
70.0	1.0	-0.00624	1.92
	1.5	1.59	-1.63
	2.0	0.00757	0.00425
Average value		**1.97**	**1.81**

Table 2. Increasing of percentage yield difference under various operating conditions of a pineapple juice extractor at three extraction periods.

Extraction time (min)	Draft	Percentage yield difference at two ranges of temperature (%)	
		55.0-62.5°C	62.5-70.0°C
50	1.0	2.60	4.53
	1.5	1.85	4.64
	2.0	1.88	5.69
70	1.0	0.00242	2.53
	1.5	1.32	3.68
	2.0	1.06	3.20
90	1.0	-1.43	3.35
	1.5	0.00326	-0.00856
	2.0	-1.10	2.09
Average value		**0.68**	**3.30**

pineapple juice. Additionally, the extraction with temperature of 70.0°C and operating time of 50 min. was the best condition whilst extraction at a higher draft value has more productivity compared to those results of experiments as shown in Table 2. This yield corresponded to the results in Table 1.

6. Validation of mathematical model

All parameters determined by the equations in section 2, from 27 experiment trials were used for simulating in RCCE model. Predicted values of solute concentration in solid and liquid phase were comparative studied with the experimental values. To validate the diffusion-back-mixing model and the standard deviation in solid and liquid phase was shown in Table 3. From the results, they show that the diffusion-back-mixing model predict the evolution of mass transfer in solid phase more precise than those of liquid phase. The average standard deviation value of solid and liquid phase was about 6.45 and 8.43, respectively.

Table 4 shows the simulated and experimental values of concentration of solid and liquid phase during extraction time of 0-51.3 min. in the experiment test no.1. The results indicate that at the beginning of extraction period, the concentration of solute in solid and liquid phase of predicted values have a good agreement with the experimental values. In contrary, after extraction time over 30 min., the predicted concentration of solute in both phases was significantly lower than the experimental values. This may be because of inconsistency of the Peclet number in the extraction screw, especially at the leaving end of extraction unit. To clarify the phenomena, it found

Table 3. Evaluation of simulated and experimental results among various operating conditions

Experimental results									SD in solid phase	SD in liquid phase
Exp. no.	Draft (α)	T (°C)	Time (min)	K_x	Bi	x_f (kg/m^3)	y_f (kg/m^3)	Yield %		
1	1.41	55.0	50	5.17	4.25	100.3	40.5	59.6	3.9	6.1
2	1.18	55.0	70	4.76	3.21	101.7	38.7	61.9	4.8	8.8
3	1.16	55.0	90	4.20	2.40	100.9	36.7	63.7	5.2	8.8
4	1.76	55.0	50	5.55	5.80	96.6	35.1	63.7	6.2	5.5
5	1.69	55.0	70	4.55	3.21	97.5	34.2	65.0	3.8	7.4
6	1.67	55.0	90	3.87	2.25	97.9	31.8	67.5	4.0	8.8
7	2.17	55.0	50	5.25	5.14	89.9	31.5	65.0	4.6	7.7
8	2.21	55.0	70	4.47	3.67	96.3	31.2	67.7	5.9	8.5
9	1.98	55.0	90	3.80	2.25	96.4	28.7	70.2	6.8	8.5
10	1.28	62.5	50	6.83	5.31	93.3	36.3	61.1	4.8	7.9
11	1.15	62.5	70	5.42	2.73	96.4	36.6	62.1	5.0	10.6
12	1.10	62.5	90	4.95	2.23	97.5	36.3	62.7	7.4	9.3
13	1.58	62.5	50	8.17	14.6	100.7	35.4	64.9	7.6	6.3
14	1.45	62.5	70	5.42	2.94	96.2	32.9	65.8	4.9	7.6
15	1.44	62.5	90	4.83	2.29	100.2	32.3	67.7	6.8	7.5
16	2.21	62.5	50	7.42	9.58	94.7	31.9	66.3	6.00	7.2
17	1.99	62.5	70	5.07	2.74	101.0	31.9	68.4	8.6	7.7
18	1.84	62.5	90	4.40	2.02	98.9	30.3	69.4	7.2	10.7
19	1.24	70.0	50	9.08	8.75	99.1	35.6	64.0	6.7	7.9
20	1.10	70.0	70	5.82	2.26	95.7	34.8	63.6	7.1	8.8
21	.11	70.0	90	5.00	1.71	97.0	34.1	64.9	7.8	8.9
22	1.62	70.0	70	9.99	22.8	104.3	34.2	67.2	8.6	8.3
23	1.52	70.0	70	7.05	3.89	103.7	32.9	68.3	8.4	9.2
24	1.52	70.0	90	5.43	2.15	100.5	33.0	67.2	7.7	11.9
25	2.10	70.0	50	8.33	7.81	98.6	29.5	70.0	8.8	7.0
26	1.75	70.0	70	6.56	3.38	96.3	28.3	70.6	7.5	10.9
27	1.51	70.0	90	5.62	2.3	98.7	28.7	70.9	8.1	9.9
Average value				**5.6**	**5.0**	**98.2**	**33.5**	**65.9**	**6.45**	**8.43**

that during extraction, concentration of solute in liquid phase at the leaving end (Position no.6 in Figure 3) was determined, opposite to the assumption of model (Peclet number was constant and relatively low due to diffusion back-mixing incidence). However, the conclusion shows that for the solid phase, most of the predicted values corresponded to the experimental values while for the liquid phase, the simulated results were slightly lower than those results of experiments at long operating period as clearly shown in Table 4 and Figure 5.

Consequently, percentage yields of all experiments were not greater than 70%. This may be clearly explained by considering the simulated results of the diffusion back-mixing model as follows.

Figures 6 and 7 illustrate the yield as related to Biot number, R value and total extraction time under the condition of 62.5°C; as predicted by the diffusion-back-mixing model. Although it was seem that, in general, Biot number exhibited stronger effect on the yield than that of R value, the fact that Bi > 4 for all extraction trials indicated it weaker effect. On the other hand, as we found that R has a magnitude around 1.5-3.5, from Figure 5, if time restricted the total extraction time to lower than 90 min, the yield was lower than 80% of total juice even if the Bi number was infinite. Thus, it was due to the fact that the combined effect of finite Bi number and a high back-mixing that limited the yield to about 70% for all our extraction trials.

Table 4. Comparison of back-mixing simulated values and experimental values for concentration of solid and liquid phase of Test no.1. [Extraction time and temperature of 50 min. and 55°C, Draft of 1.41]

Time (min)	Concentration in solid phase (kg/m^3)		Concentration in liquid phase (kg/m^3)	
	Experimental value	*Predicted value*	*Experimental value*	*Predicted value*
0.0	100.3	100.3	50.8	50.9
5.7	92.1	87.3	49.7	51.3
17.1	76.1	71.0	43.4	45.7
28.5	63.6	60.2	34.9	39.8
39.9	52.5	52.3	26.0	22.9
51.3	42.4	48.6	17.2	10.1

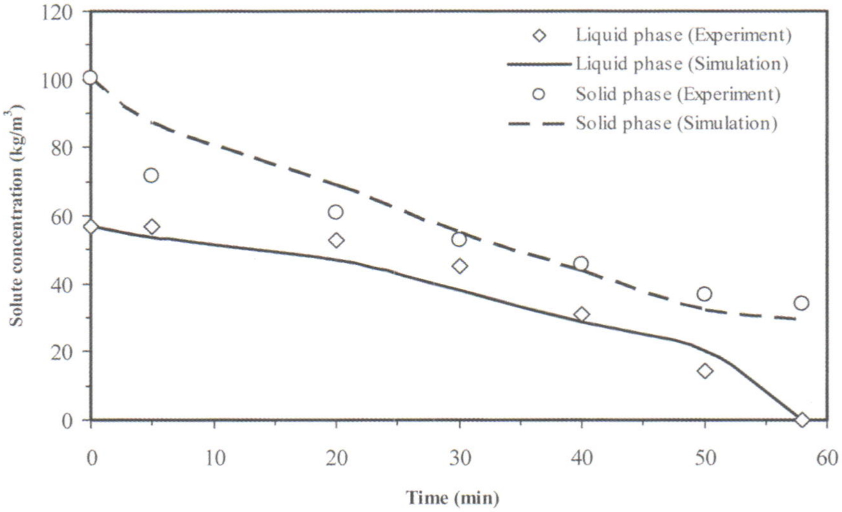

Figure 5. Illustration of solute concentration of simulated and experimental results of Test no.15 [Extraction time and temperature of 90 min. and 62.5°C, Draft of 1.44]

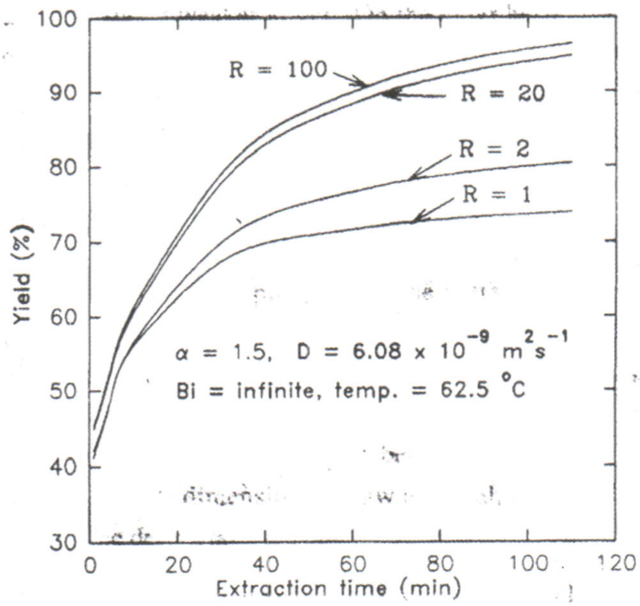

Figure 6. Percentage of yield among the extraction period at various R-values.

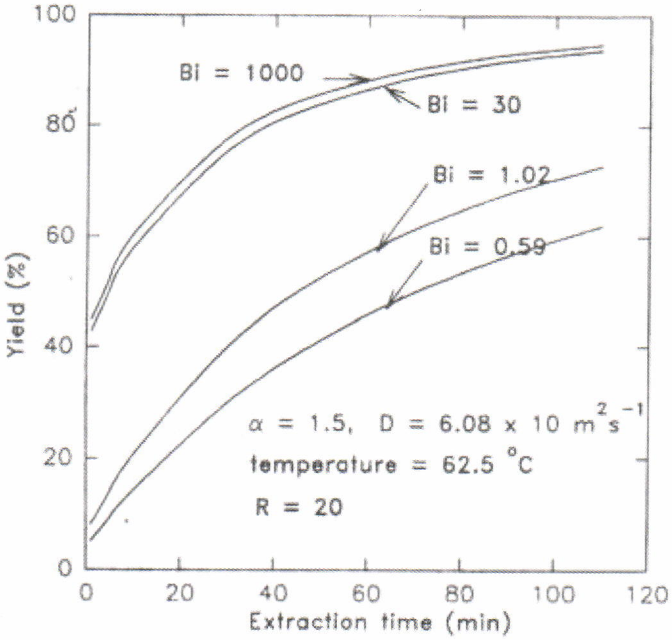

Figure 7. Percentage of yield among extraction time at various Bi numbers.

Conclusion

Based on the experimental and simulated results of this study, the following conclusions were reported :

1. The efficiency of the system can be improved by reducing axial dispersion while promoting the local mixing. This may be achieved by increasing the length of the trough while keeping the total extraction time constant.
2. Diffusion coefficient and time delayed due to plasmolysis are dependent on extraction temperature and structure of pineapple peel before extraction
3. At a lower Biot number, total mass transfer coefficient from surface of solid phase to liquid phase has a relatively low compared to those of a higher Biot number. Consequently, Biot number is more effective on extraction than the Peclet number of liquid phase.
4. Percentage yield is directly related to temperature and draft value whilst it is insignificantly affected by extraction time.
5. The simplified diffusion-back-mixing model has a good agreement to the experimental data, especially on solid phase. The design requires only batch extraction trials.
6. Pineapple juice from peel using the SME size extractor is attractive and can make a value-added from agriculture waste.

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Nomenclatures

a	characteristic length of a solid particle, m
Bi	Biot number = ka/D
D	solute diffusivity in solid particles, m^2/s
D_x, D_y	volumetric dispersion coefficient in solid and liquid phase, respectively, m^6/s
K, k	overall and film mass transfer coefficient, respectively, s^{-1}
L	(volumetric flow rate of liquid phase), m^3/s
M	equilibrium distribution constant, decimal
P	Peclet number of solid phase, dimensionless
R	volumetric flow rate of liquid phase, m^3/s
S	volumetric flow rate of solid phase, m^3/s
S_h	Sherwood number, dimensionless
T	time delayed due to plasmolysis, s
T	temperature, °C
t_f	is theoretical extraction time, $t_f = t+t_1-t_p$
t	is the actual extraction time, s
t_t and t_p	are time lead due to initial solute distribution in solid and time delayed due to plasmolysis, respectively
Y	solute concentration in liquid at time t or at position z
v	shape index = 1, 2, 3 infinite slab, infinite cylinder and sphere respectively.
V	cumulative volume and total volume of solid phase, respectively, m^3 average solute concentration in solid at time t or at position z k m
α	Draft, Lm/s

Subscripts

x, y	solid and liquid phase
abs	absolute temperature

References

Agricultural Statistics No.403, in Thailand Foreign Agricultural Trade Statistics 2004. (2005). Center for Agricultural Information, Office of a Agricultural Economics, Ministry of Agricultural & Co-operatives, Bangkok, Thailand, 4213 pages.

Avila, I.M.L.B and Silva, C.L.M. (1999). Modeling kinetics of thermal degradation of color in peach puree. J. of Food Eng. 39(2), 161-166.

Barreiro, J.A., Milano, M. and Sandoval, A.J. (1997). Kinetics of color change of double concentrated tomato paste during thermal treatment. J. of Food Eng. 33(3-4), 359-371.

Beristain, C.J., Asuara, E., Cortes, R. and Garicia, H.S. (1990). Mass Transfer During Osmotic Dehydration of Pineappple rings.

Int. J. of Food Sci.&Technol. 25, 576-582.

Beveridge, T. and Harrison, J.E. (1984). Nonenzymatic browning in pear juice concentrate at elevated temperatures. J. of Food Eng. 49(5), 1335-1340.

Bioquip. (1984). The application of Bioguip counter-current extractor to the commercial production of apple juice by continuous diffusion extraction. Bioquip Australia Ply Ltd., NSW, Australia.

Bunlonluer, S. (1994). Fruit juice industry. Settatasna, 12 (May-June), 6-22. (in Thai).

Casimir, D.J. (1983). Counter-current extraction of soluble solids from foods. CSIRO Fd. Res. Quar. 53(2), 38-43.

Gunasekaran, S., Fisher, R.J. and Casimir, D.J. (1989). Predicting soluble solids extraction from fruits in a reversing, single screw counter current diffusion extractor. J. Food Sci. 5(54), 1261-1265.

Lee Y.C. and Schwartzberg, H.G. (1990). Effect of axial dispersion during solid-liquid extraction, engineering and food vol.3. Spiess, W.E.L. and Schubert, H. (ed), Elsevier, London, 1-10.

Marisa, R., Chiewchan, N. and Srichumpoung, W. (2005). Effect of thermal processing on the quality loss of pineapple juice. J. of Food Eng. 66, 259-265.

Mecklenburgh, J.G. and Hartland, S. (1975). The theory of backmixing. John-Wiley & Sons, London.

Siripatana, C. (1986). Mass transfer in a reversing counter-current extractor. Master of Applied Science thesis, UNSE, Australia.

Siripatana, C. (1997). Solute diffusion in fruit, vegetable and cereal processing I: simplified solutions for diffusion in anomalous shapes. Songklanakarin J.Sci. Technol.

Siripatana, C. and Suparanon, N. (1997). Solute diffusion in fruit, vegetable and cereal processing II: simplification of diffusion equation and development of mathematical model. Songklanakarin J.Sci. Technol.

Sodchit, C. (1993). Machanism of chemical and physical changes of osmotic dehydrated pineapple. Master of Science thesis, Prince of Songkla University, Thailand, 185 pages [in Thai].

Spanink, J.A.M. (1983). Calculation method for solid-liquid extractots, Progress in food engineering. C. Canterelli and C. Peri (ed), Foster-Verleg AG/Foster, 109-125.

Thummadetsak, T. (1996). Mass transfer in pineapple juice extractor. Master of Chemical Engineering thesis, Faculty of Engineering, Prince of Songkla University, Hat-Yai, Songkhla, 274 pages [in Thai].

Tirawanichakul S., Prachayawarakorn S., Varunyanond W., Tungtrakul P. and Soponronnarit S. (2004). Effect of fluidized bed drying temperature on various quality attributes of paddy. Int. J. of Drying Technol. 22(7), 1731-1754.

Tirawanichakul, S., Siripatana, C., Thong U-rai, C. and Prasarnparn, S. (1996). Development juice extraction system from pineapple peel using reversing counter current type and high performance extrusion process. Research report, (National research grant), 245 pages [in Thai].

Tirawanichakul, Y., Prachayawarakorn, S., Tangtrakul, P., Chaiwatpongsakorn, P. and Soponronnarit, S. (2003). Experiment on in-store paddy drying under tropical climate: simulation and product quality. Int. J. of Drying Technol. 21(6), 1049-1065.