CHAPTER IV
RESULTS AND DISCUSSION

The multistage foam fractionator used in this study was first put through a series of tests in order to check when steady state could be established. Operating under the base conditions, the foam fractionation unit has been shown to reach steady state within approximately 6 hours. After this period of time, the surfactant concentration measured in each tray from the sampling port became constant, meaning that the steady state was established as shown in Figure 4.1.

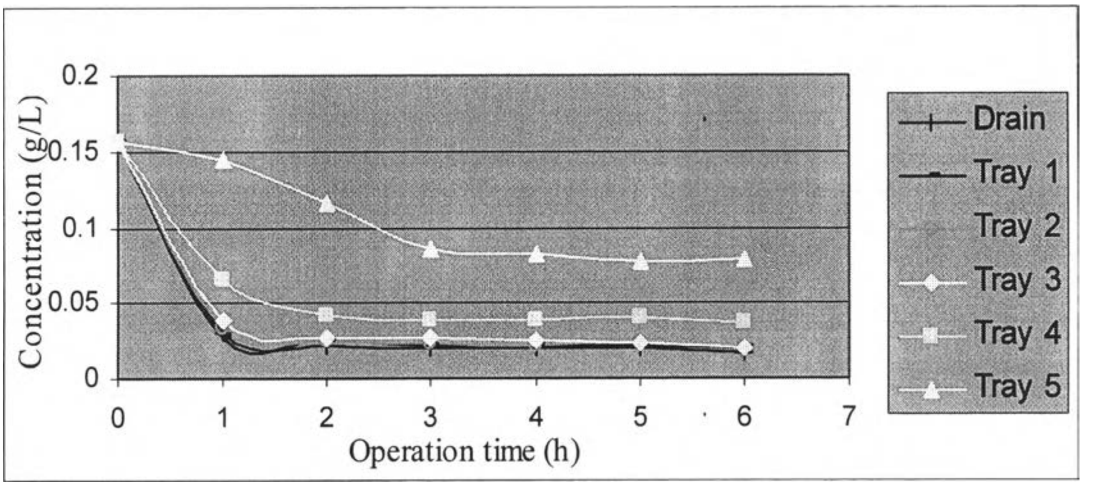


Figure 4.1 The surfactant concentration measured in each tray versus time.

After the steady state was established, effects of several parameters on the separation efficiency of the multistage fractionator operated in a continuous mode of operation were studied and evaluated in terms of surfactant recovery (%) and enrichment ratio as shown below:

$$\text{Surfactant Recovery (\%)} = \frac{C_i - C_e}{C_i} * 100$$

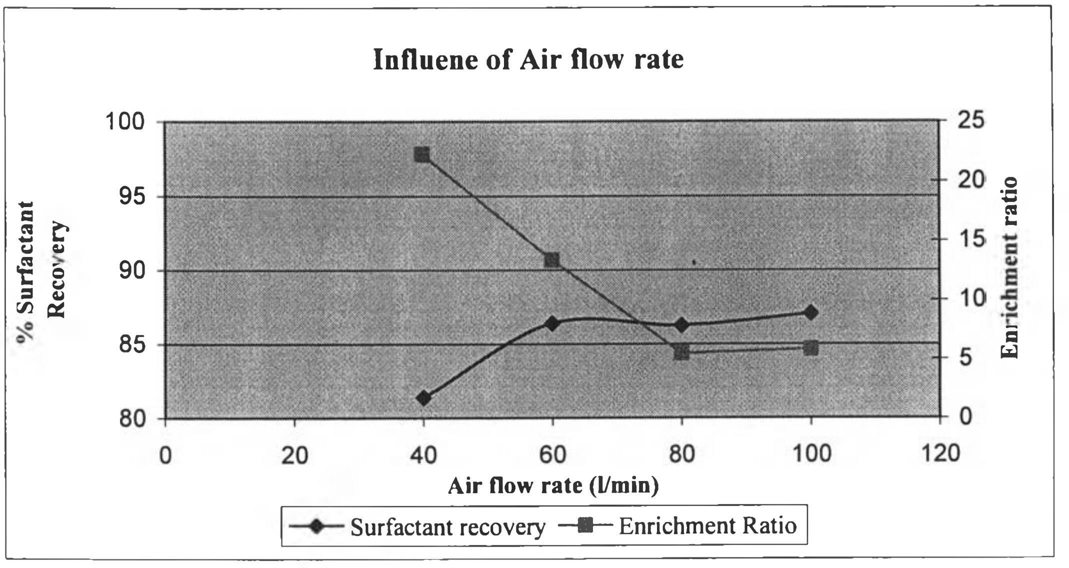
$$\text{Enrichment Ratio} = C_f / C_i$$

C_i and C_e are surfactant concentrations (mg/L) in the influent and effluent streams, respectively, and C_f is the surfactant concentration in the foam concentrated phase.

It is important to note that once the surfactant concentrations in all streams were measured, mass balance on the fractionator could be performed on the fractionator. It was found that the mass balance for surfactant was closed within at least 90% for all runs. The deviation mainly came from a fluctuation in foam flow rate and low surfactant concentration in the effluent liquid stream. Subsequently, effects of various parameters such as the air flow rate, the height of foam, tray spacing, the surfactant loading in the feed and the feed flow rate were studied independently.

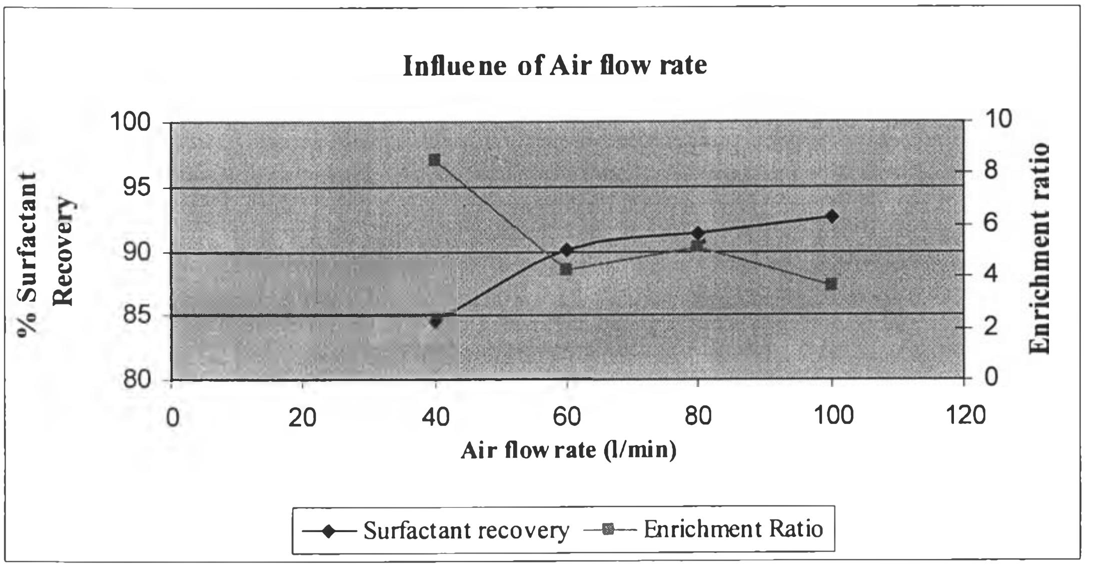
4.1 Effect of Air Flow Rate

The effect of the air flow rate on the surfactant recovery using a multistage foam fractionator at various surfactant feed concentrations is shown in Figures 4.2-4.5. The experiments were carefully designed such that the lowest air flow rate used in this part of the study was very close to the lowest flow rate possibly used for this multistage foam fractionator. Any flow rate lower than this would have resulted in such a low production of foam that foam being produced would collapse before reaching the overhead draw-off. From Figures 4.2-4.5, it can be seen that increasing air flow rate resulted in a reduction in the enrichment ratio but it led to an increase in % surfactant recovery. For all conditions, the surfactant recovery was in the range of 80-95% whereas the enrichment ratio was in the range of 2-20. When comparing among various flow rates used, the highest enrichment ratio was obtained at the lowest air flow rate used which was 40 ml/min. At this air flow rate the enrichment ratio as high as 20 was obtained when the CPC concentration in the feed was lowest (0.25 CMC) as seen in Figure 4.2. In contrast, when air flow rate was increased, better surfactant recovery was observed as seen that the surfactant recovery (%) as high as 90-95% could be achieved in almost all conditions studied. An increase in the air flow rate increases the interfacial area between gas and liquid and the mass transfer, thus increasing the surfactant recovery. However, increasing air flow rate tends to generate wet foam which contains low amount of surfactant, resulting in low enrichment ratio.



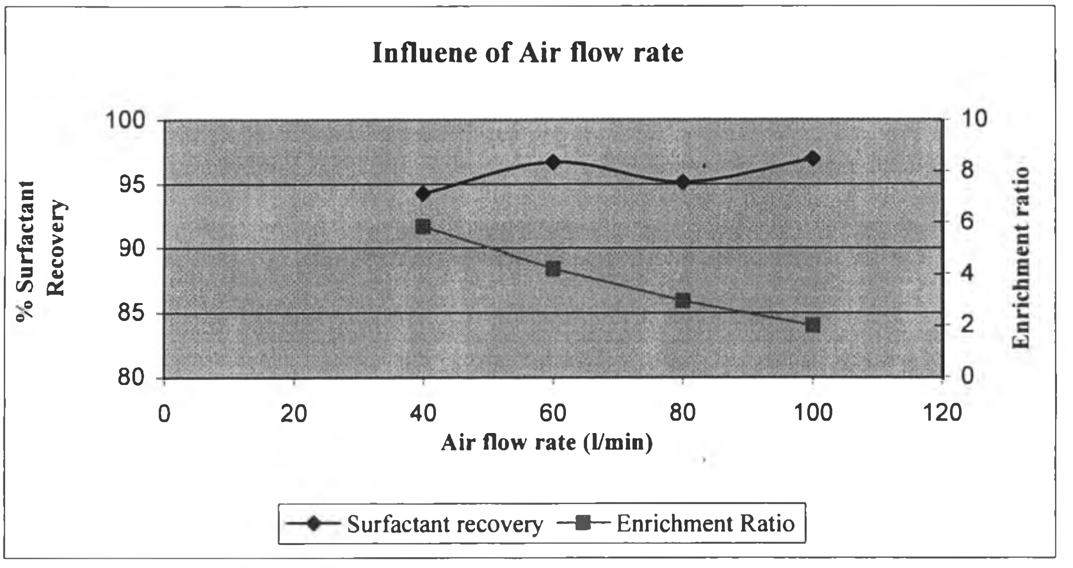
Condition: [CPC] = 0.25 CMC; Feed flow rate = 50 ml/min; Foam height= 30 cm; tray spacing =15 cm and No. of tray = 5

Figure 4.2 The effect of superficial air velocity under the base case conditions and at [CPC] = 0.25 CMC.



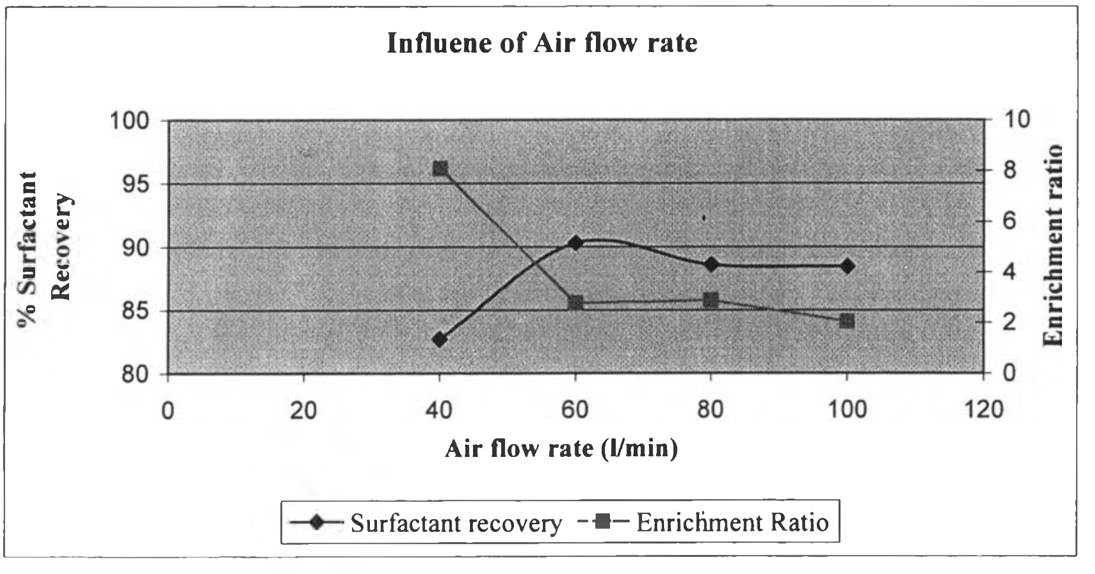
Condition: [CPC] = 0.5 CMC; Feed flow rate = 50 ml/min; Foam height= 30 cm, tray spacing =15 cm and No. of tray = 5

Figure 4.3 The effect of superficial air velocity under the base case conditions and at [CPC] = 0.5 CMC.



Condition: [CPC] = 0.75 CMC; Feed flow rate = 50 ml/min; Foam height= 30 cm; tray spacing =15 cm and No. of tray = 5

Figure 4.4 The effect of superficial air velocity under the base case conditions and at [CPC] = 0.75 CMC.

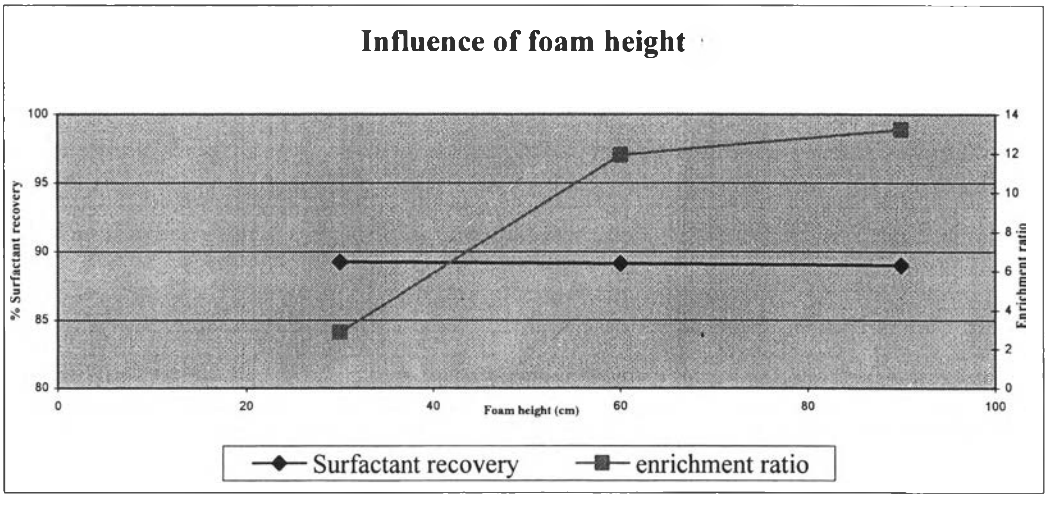


Condition: [CPC] = 1.0 CMC; Feed flow rate = 50 ml/min; Foam height= 30 cm; tray spacing =30 cm and No. of tray = 5

Figure 4.5 The effect of superficial air velocity under the base case conditions and at [CPC] = 1 CMC.

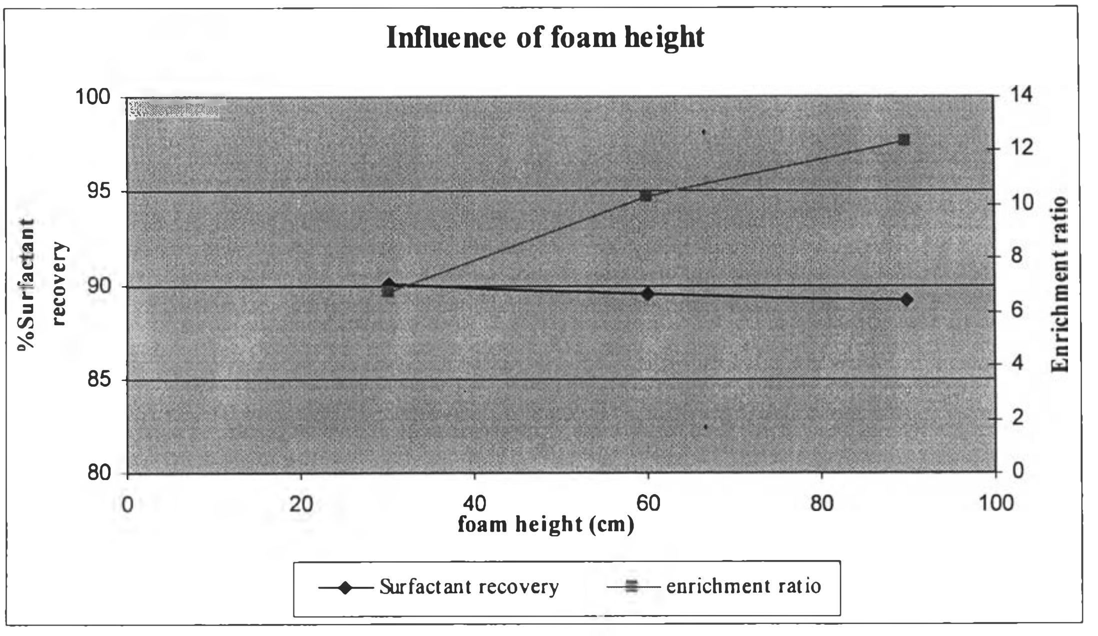
4.2 Effect of Foam Height

Effect of the foam height in the foam fractionation column was studied by varying a distance between the surface of liquid in the highest tray and the foam draw-off pipe as shown in Figures 4.6-4.8. For this study, the feed concentration of 0.25 CMC was not included since the concentration was too low to produce foam enough to reach 90 cm height. From Figures 4.6-4.8, it can be seen that increasing foam height resulted in an increase in the enrichment ratio but has little effect on the surfactant recovery. For all conditions, the surfactant recovery was approximately 90% whereas the enrichment ratio was in the range of 4-12. Among three foam heights studied (30, 60, and 90 cm), the foam height at 90 cm gave the highest enrichment ratio for all concentrations studied. Increasing foam height leads to longer foam residence time, which allows more drainage of the liquid in the films. Thus, the concentration of the adsorbed surfactant molecules increases as foam height increases, resulting in higher enrichment ratio. On a contrary, within the range of foam heights investigated here, the effect of foam height on the surfactant recovery was not as significant as observed with the enrichment ratio. The surfactant recovery was found to be approximately 90% for all cases.



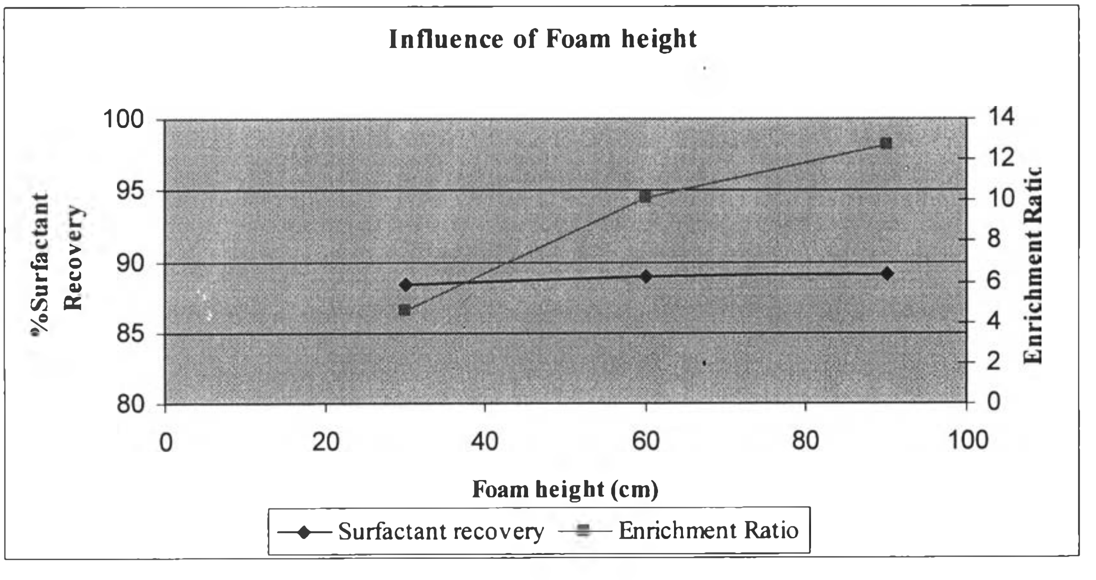
Conditions: [CPC] = 0.5 CMC; Air flow rate = 80 L/min; Feed flow rate = 50 ml/min; tray spacing = 30 cm and No. of tray =5

Figure 4.6 The effect of foam height on surfactant recovery and enrichment ratio and at [CPC] = 0.5 CMC.



Conditions: [CPC] = 0.75 CMC; Air flow rate = 60 L/min; Feed flow rate = 50 ml/min; tray spacing =30 cm and No. of tray =5

Figure 4.7 The effect of foam height on surfactant recovery and enrichment ratio and at [CPC] = 0.75 CMC.

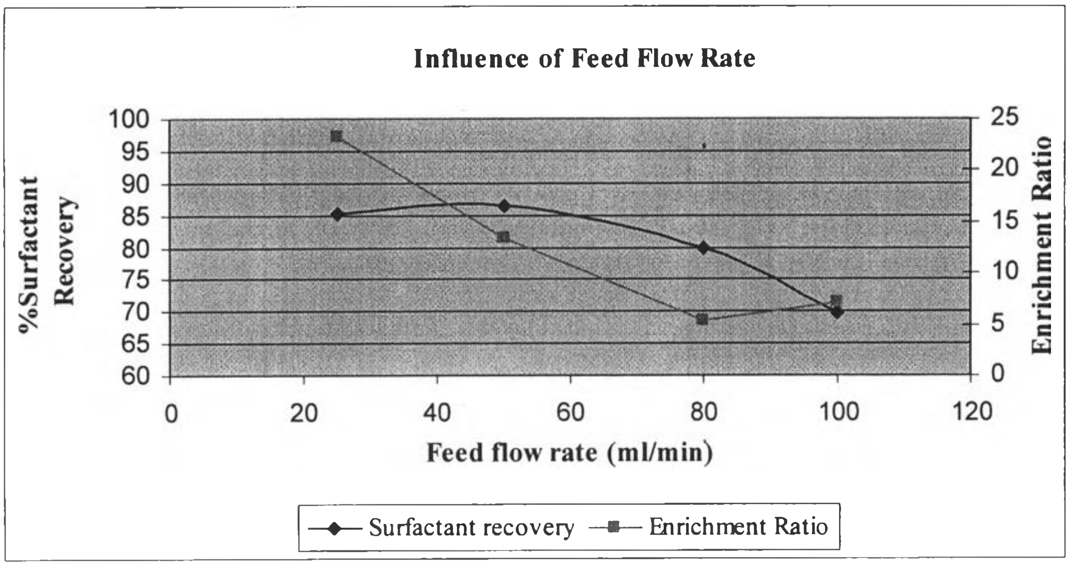


Conditions: [CPC] = 1 CMC; Air flow rate = 40 L/min; Feed flow rate = 25 ml/min; tray spacing =30 cm and No. of tray =5

Figure 4.8 The effect of foam height on surfactant recovery and enrichment ratio and at [CPC] = 1 CMC.

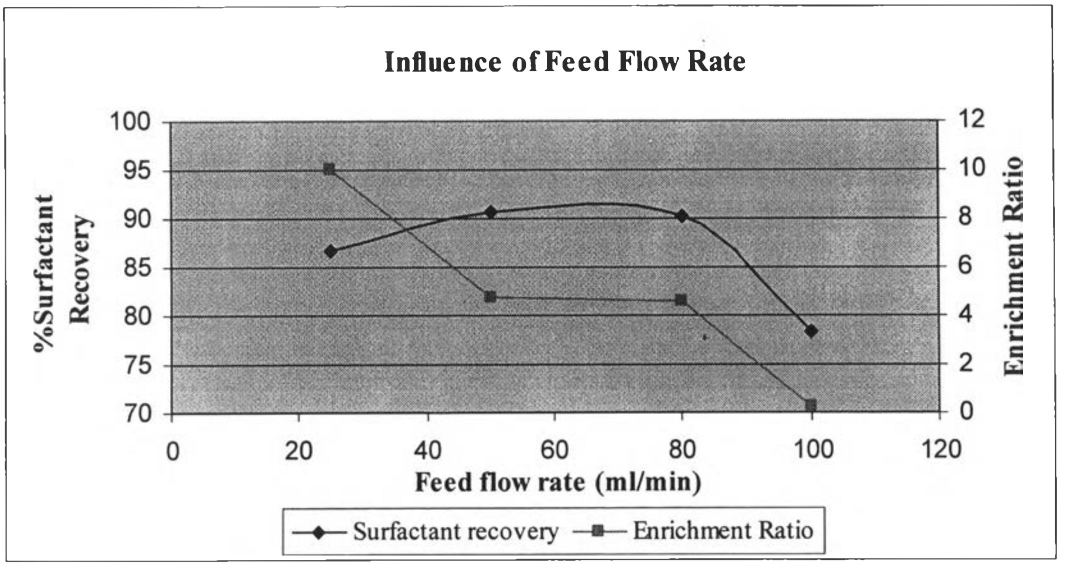
4.3 Effect of Liquid Feed Flow Rate

Figures 4.9-4.12 show the effect of liquid feed flow rate on the surfactant recovery and enrichment ratio at different surfactant concentrations in the feed. From these figures, it can be seen that increasing liquid feed flow rate resulted in a decreasing in both enrichment ratio and surfactant recovery. For all conditions studied, the surfactant recovery was in the range of 70-95 % whereas the enrichment ratio was in the range of 2-20. The enrichment ratio and the surfactant recovery as high as 20 and 95%, respectively, were obtained at the lowest feed flow rate of 25 ml/min. The decrease in the enrichment ratio and surfactant recovery upon increasing flow rate of the liquid feed can be attributed to the shorter residence time at higher liquid flow rate. As a result, considerable amount of surfactant still remains in the liquid which drains out of the column.



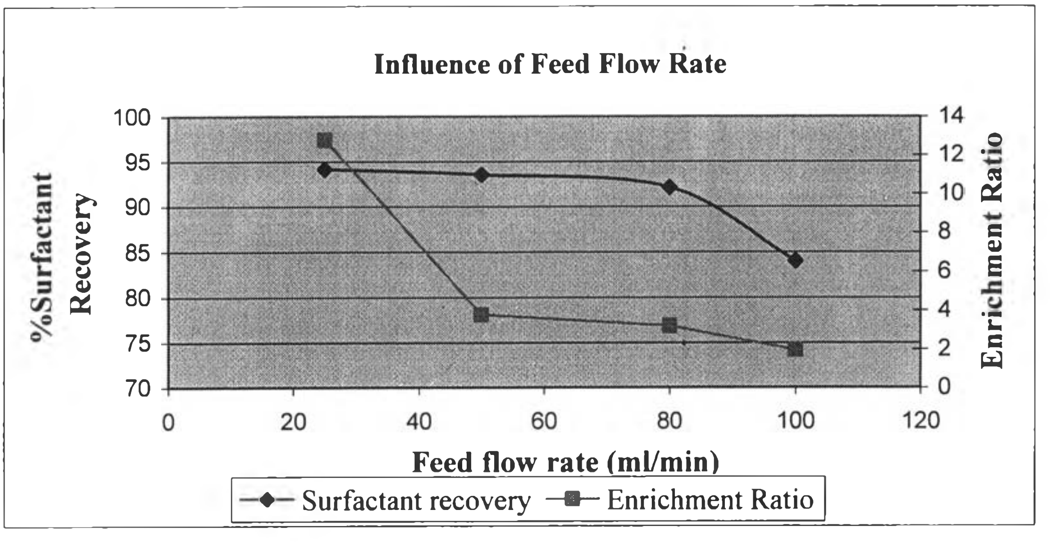
Condition: [CPC] = 0.25 CMC; Air flow rate = 60 L/min; foam height = 30 cm; tray spacing = 15 cm and No. of tray = 5

Figure 4.9 The effect of liquid feed flow rate under the base case conditions and at [CPC] = 0.25 CMC.



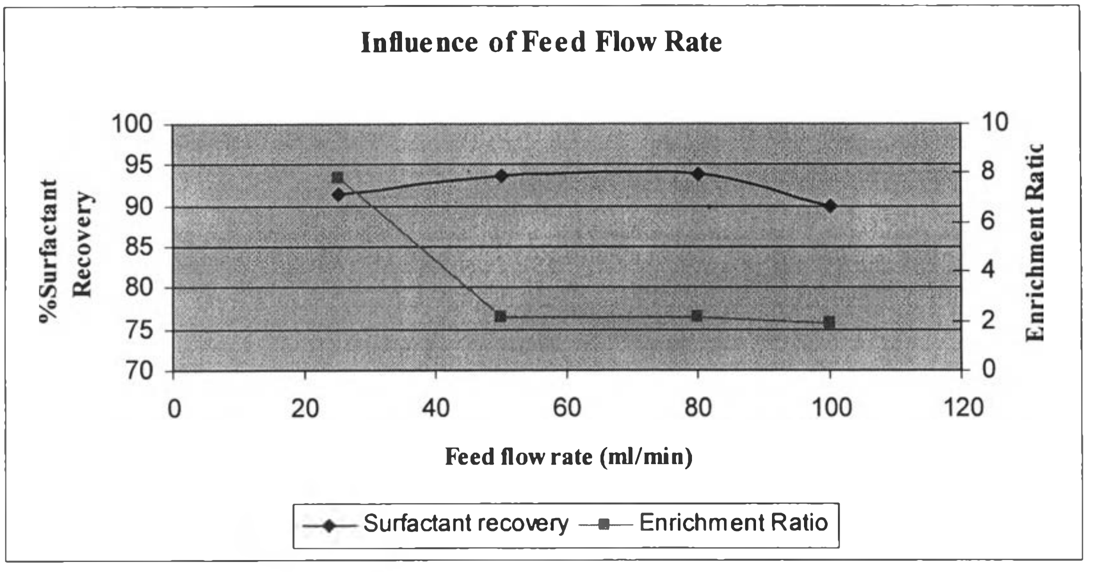
Condition: [CPC] = 0.50 CMC; Air flow rate = 40 L/min; foam height = 30 cm; tray spacing = 15 cm and No. of tray = 5

Figure 4.10 The effect of liquid feed flow rate under the base case conditions and at [CPC] = 0.5 CMC.



Condition: [CPC] = 0.75 CMC; Air flow rate = 40 L/min; foam height = 60 cm; tray spacing = 15 cm and No. of tray = 5

Figure 4.11 The effect of liquid feed flow rate under the base case conditions and at [CPC] = 0.75 CMC.



Condition: [CPC] = 1.0 CMC; Air flow rate = 40 L/min; foam height = 30 cm; tray spacing = 30 cm and No. of tray = 5

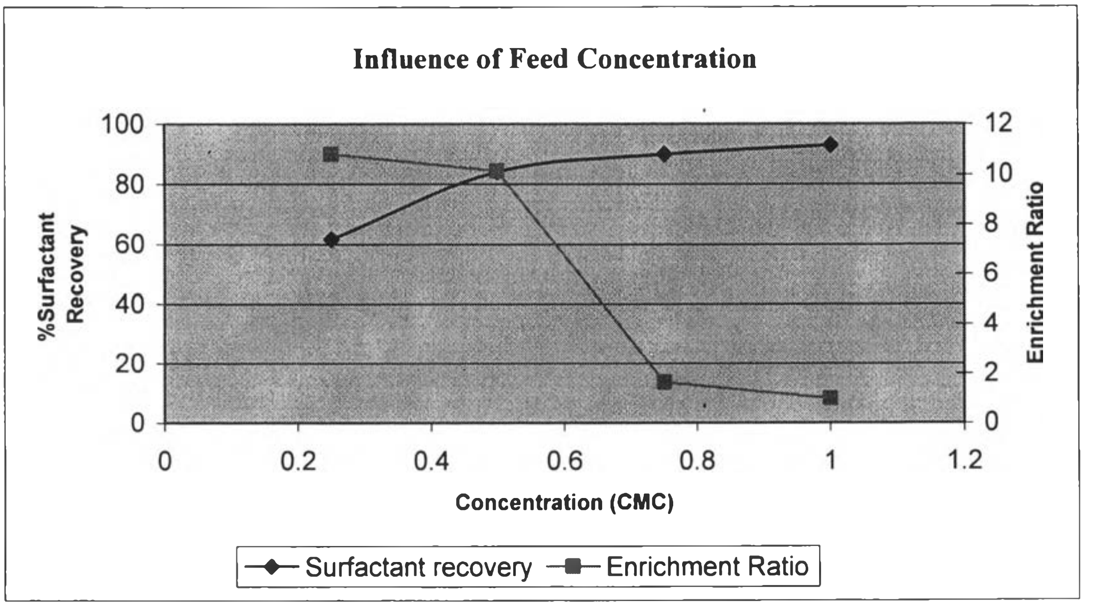
Figure 4.12 The effect of liquid feed flow rate under the base case conditions and at [CPC] = 1 CMC.

4.4 Effect of Feed Concentration

The effect of the surfactant concentration in the influent on the performance of the multistage foam fractionator is shown in Figure 4.13. The concentration of the surfactant in the feed solution was varied in the range of 25-100% of the CMC of CPC. From this figure, it can be seen that increasing surfactant concentration from 0.25 CMC to 1 CMC resulted in a drastical decrease in the enrichment ratio from approximately 10 to less than 2. In contrast, within the same range of the surfactant feed concentration, the surfactant recovery increased from 60% to almost 95%. High surfactant concentration in the thin liquid film in the foam lamellae may make this liquid more structured or cause an increase in surface viscosity and surface concentration, leading to a decrease in the rate of film drainage, thus causing the surfactant to quickly go out off the column. On the other hand, foam that formed over a fluid with low surfactant concentration is less stable and results in a much higher enrichment ratio than that formed over high-surfactant fluid. The foam formed over a fluid with higher concentration is characterized by smaller, more stable bubbles. This could also explain the increasing volumetric foam production with increasing surfactant feed concentration as seen in Fig. 4.13. The enrichment ratio increases as feed liquid surfactant concentration decreases, presumably due to the increased ratio of bubble surface area to surfactant in the liquid.

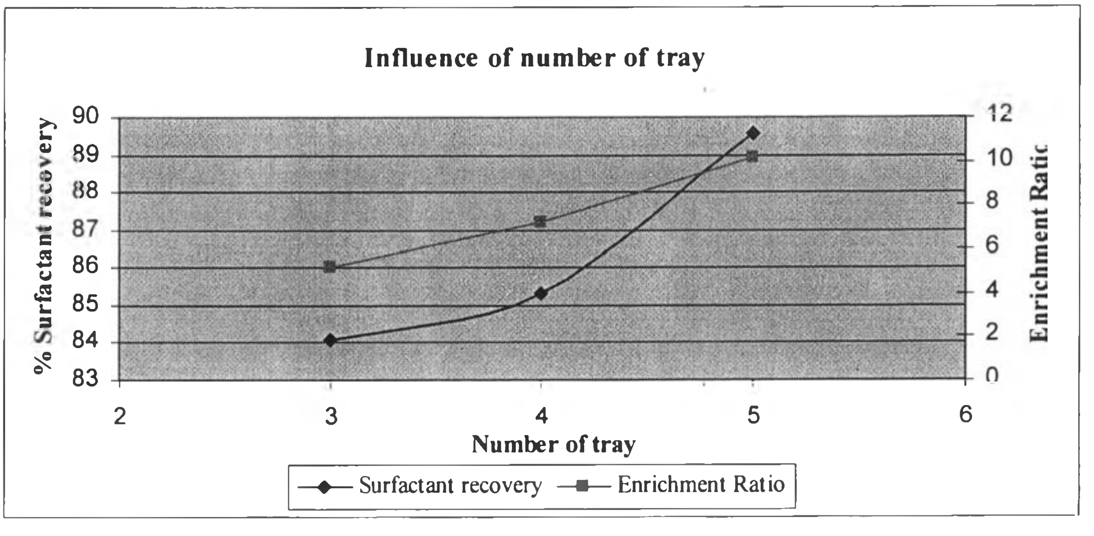
4.5 Effect of Number of Trays

The effect of number of trays on surfactant recovery and enrichment ratio is shown in Figure 4.14. It can be seen that increasing number of trays from 3 to 5 resulted in an increase in both enrichment ratio and surfactant recovery. Under the conditions studied, the highest % surfactant recovery of 90 % and enrichment ratio of 10 was achieved when 5 trays were used. This is due to the fact that increasing number of trays provides longer residence time and, consequently, allowing the surfactant to become more concentrated at the higher trays.



Condition: Air flow rate =50 L/min; Feed flow rate = 50 ml/min; foam height = 60 cm; tray spacing = 30 cm and No. of tray =3

Figure 4.13 Influence of influent concentration.



Condition: [CPC] = 0.5 CMC; Air flow rate =40 L/min; Feed flow rate = 50 ml/min; foam height = 30 cm; and tray spacing = 30 cm

Figure 4.14 Influence of Number of tray.

4.6 Effect of Recycle Position and Recycle Ratio

After the steady state operation was first acheieved in the fractionation column, the position of the liquid feed was changed to the other tray and the operation was continued until the steady state was re-established. The sample was then taken and analyzed for the surfactant concentration. In addition, in another set of experiments a portion of the effluent was recycled back to the column in order to examine its effect of recycle on the column performance. The recycle ratio is defined as the ratio of the liquid flow rate recycled to the column to the effluent flow rate. The results are summarized as illustrated in Table 4.1.

Table 4.1 Influence of recycle feed and feed position .

		% Surfactant Recovery		Enrichment Ratio	
Position	Concentration before recycle (g/L)	No recycle	Recycle (1:1)	No recycle	Recycle
tray5	0.9587	86.42	84.33	6.57	12.16
tray4	0.5463	89.13	83.76	10.14	14.18
tray3	0.3756	89.47	81.78	6.57	12.15
tray2	0.3757	88.57	84.53	10.22	9.32
tray1	0.3595	85.05	84.46	9.21	11.53

Condition: Air flow rate =40 L/min; Feed flow rate = 50 ml/min; foam height = 30 cm; tray spacing = 15 cm; recycle ratio 1:1and No. of tray =5

It can be seen that the change in recycle position and recycle ratio of the effluent had only little effect on both surfactant recovery and enrichment ratio. However, slight increase in the enrichment ratio was observed when the recycle feed was fed into the trays at higher position (trays 4 and 5). Therefore the effect of recycle ratio was further studied by using 3 different ratios (3/1, 1/1, and 1/3) as shown in Table 4.2. It can still be seen that no significant change was observed upon varying the recycle ratio. The results suggested that the recycle feed position and recycle ratio may not have much effect on this small column.

Table 4.2 Effect of Recycle at Various Ratios on Surfactant Recovery and Enrichment Ratio.

Ratio	Feed/Recycle= 1/1				Feed/Recycle= 2/1				Feed/Recycle= 3/1			
	% Surfactant Recovery		Enrichment Ratio		% Surfactant Recovery		Enrichment Ratio		% Surfactant Recovery		Enrichment Ratio	
Position	No recycle	Recycle	No recycle	Recycle	No recycle	Recycle	No recycle	Recycle	No recycle	Recycle	No recycle	Recycle
tray5	86.42	84.33	6.57	12.16	90.86	85.31	10.14	9.62	89.69	88.62	6.26	9.53
tray4	89.13	83.76	10.14	14.18	89.54	88.69	10.95	13.24	88.69	86.54	10.25	11.24
tray3	89.47	81.78	6.57	12.15	85.67	87.56	11.65	10.29	90.29	87.65	11.76	9.11
tray2	88.57	84.53	10.22	9.32	87.93	87.23	11.88	9.85	89.36	82.62	11.24	12.54
tray1	85.05	84.46	9.21	11.53	89.95	84.29	9.85	10.35	88.27	86.81	9.55	10.89

Condition: [CPC] = 0.50 CMC Air flow rate =40 L/min; Feed flow rate = 50 ml/min; foam height = 30 cm; tray spacing = 15 cm; and No. of tray =5

4.7 Effect of Tray Spacing

In this part of the study, the effects of various parameters previously studied such as air flow rate, foam height, feed flow rate, feed concentration, and number of trays were examined using the fractionation column with different tray spacing, 30 cm, instead of 15 cm used in the previous sections. The results obtained from the two columns with different tray spacing were then compared. Figures 4.15 (a) and (b) show the effect of air flow rate obtained from the columns with tray spacing of 15 cm and 30 cm, respectively. It can be seen that the two figures showed quite similar results that increasing air flow rate resulted in a reduction in the enrichment ratio but the surfactant recovery was increased. The surfactant recovery and the enrichment ratio obtained from the columns with different tray spacing were found to be in the range of 85-95% and 2-8, respectively.

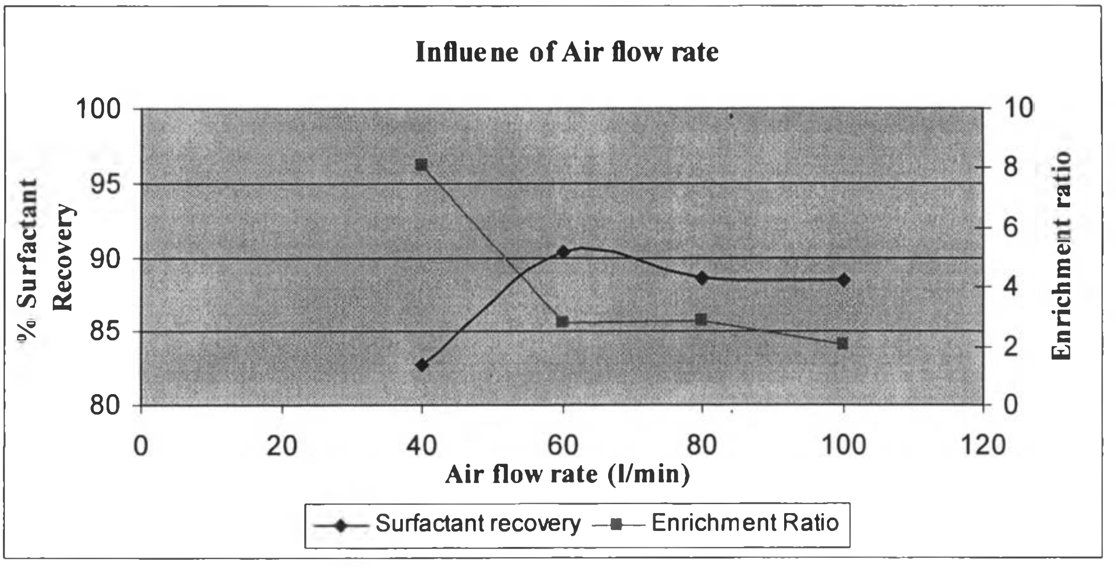
The effect of foam height on the performance of the multistage foam fractionation column with different tray spacing is shown in Figures 4.16 (a) and (b). From these figures, it can be seen that increasing foam height resulted in an increase in the enrichment ratio but did not have much effect on the surfactant recovery. When comparing between the two columns with different tray spacing, the surfactant recovery in both columns was in the same range of 90-95% whereas the enrichment ratio obtained in the column with larger tray spacing (30 cm) was slightly higher.

Figures 4.17 (a) and (b) show the effect of liquid feed flow rate on the fractionators with tray spacing of 15 and 30 cm, respectively. From these figures, the same trend was observed in both columns that increasing liquid feed flow rate resulted in a decrease in both enrichment ratio and surfactant recovery. As observed in both columns with different tray spacing, when increasing liquid feed flow rate from 25 ml/min to 100 ml/min, the surfactant recovery decreased from 80% to 95% whereas the enrichment ratio was reduced from approximately 10 to 2.

Effect of surfactant feed concentration on the multistage foam fractionation with different tray spacing is shown in Figures 4.18 (a) and (b). When comparing between the two figures, the results showed the same trend in both columns with different tray spacing that increasing surfactant concentration caused a decrease in the enrichment ratio and increase in the surfactant recovery. The surfactant recovery of as high as 95% could be achieved in both columns at the highest feed concentration (1 CMC). In contrast, the enrichment ratio of as high as 12-20 could be obtained at the lowest feed concentration (0.25 CMC).

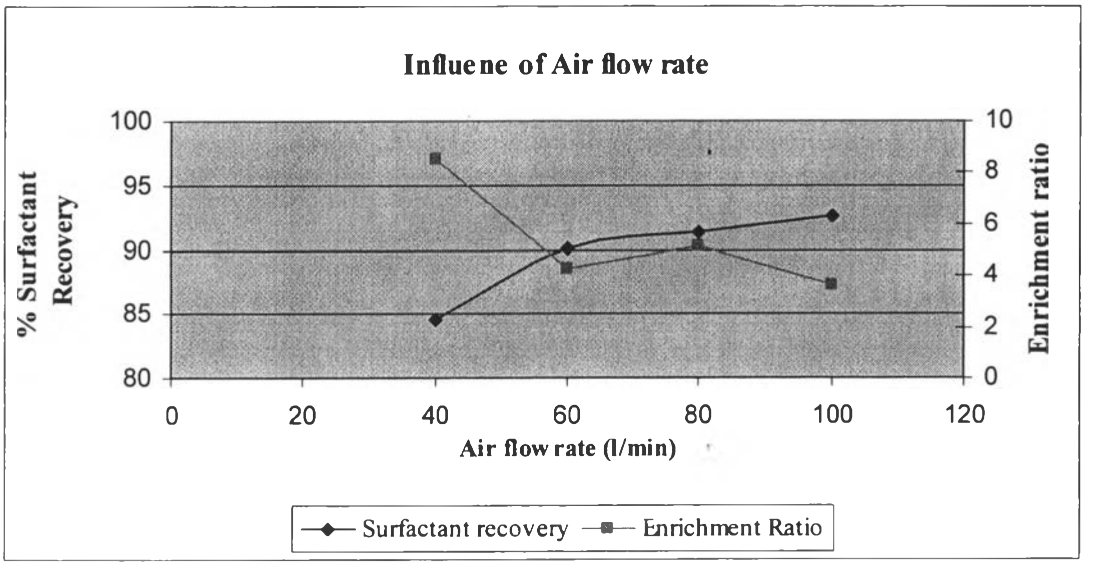
Figures 4.19 (a) and (b) show the effect of number of trays on the foam fractionation using tray spacing of 15 and 30 cm, respectively. Both figures show very similar results that increasing number of tray caused an increase in both enrichment ratio and surfactant recovery. For both columns with different tray spacing, the surfactant recovery was in the range of 80-90 % whereas the enrichment ratio was in the range of 5-15.

The results observed here indicated that under the conditions studied increasing tray spacing from 15 cm to 30 cm did not show any significant effect on the performance of the multistage foam fractionation in terms of both surfactant recovery and enrichment ratio. Very similar results and comparable values of surfactant recovery (%) and enrichment ration were obtained from the two columns using different tray spacing. This may be due to the limited size and dimension of the column which might not large enough to see the effect. In addition, the number of bubble caps on each tray may be too few which limited the extent of the mass transfer occurred in the column.



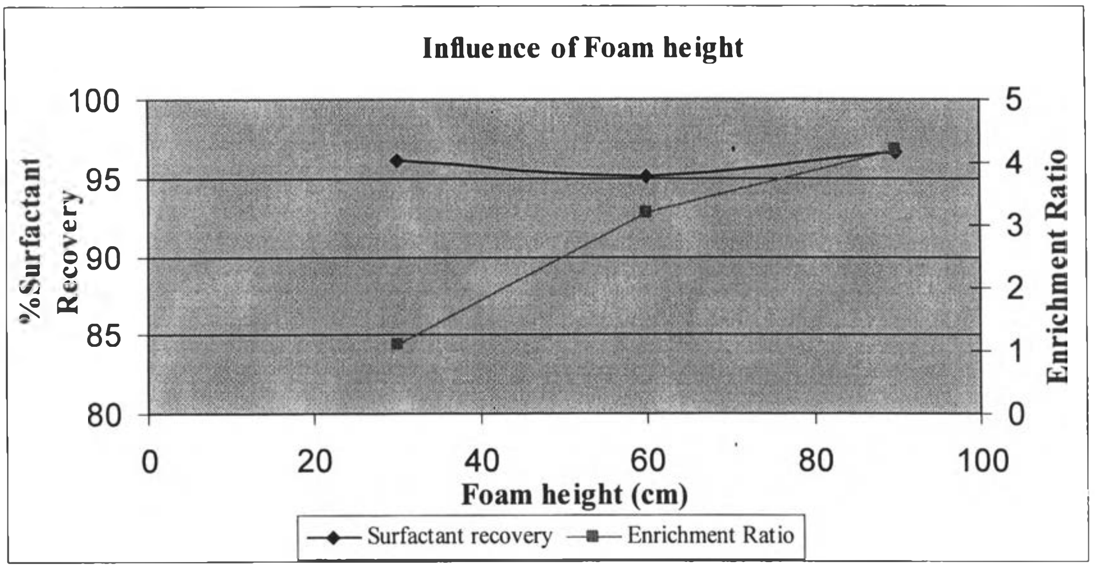
Condition: [CPC] = 0.5 CMC; Feed flow rate = 50 ml/min; Foam height= 30 cm, tray spacing =15 cm and No. of tray = 5

Figure 4.15 (a) The effect of superficial air velocity under the base case conditions and at [CPC] = 0.5 CMC.



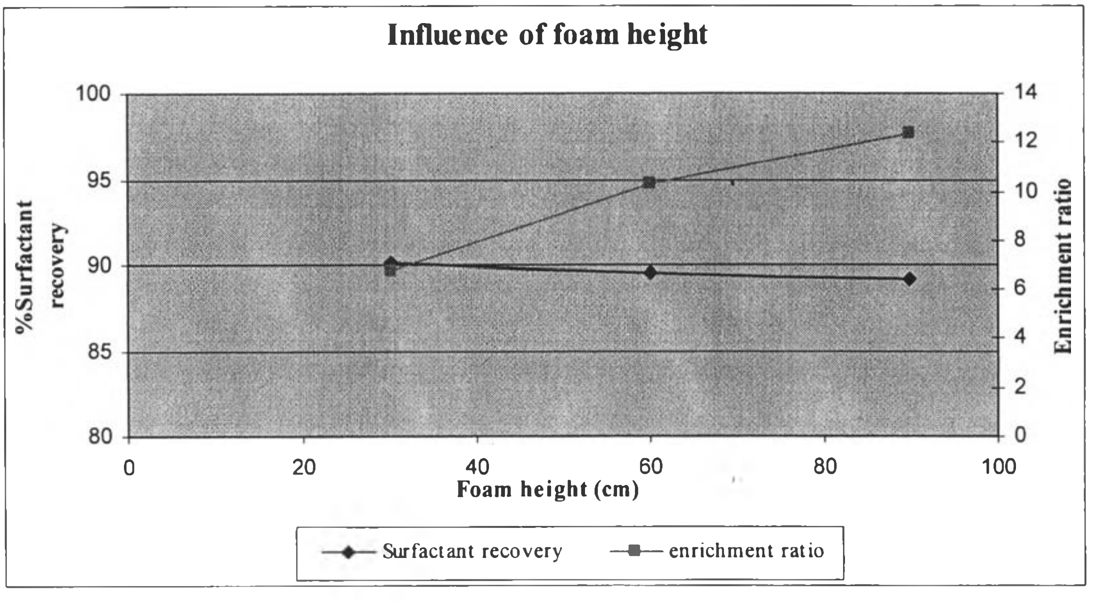
Condition: [CPC] = 0.5 CMC; Feed flow rate = 50 ml/min; Foam height= 30 cm, tray spacing =30 cm and No. of tray = 5

Figure 4.15 (b) The effect of superficial air velocity under the base case conditions and at [CPC] = 0.5 CMC.



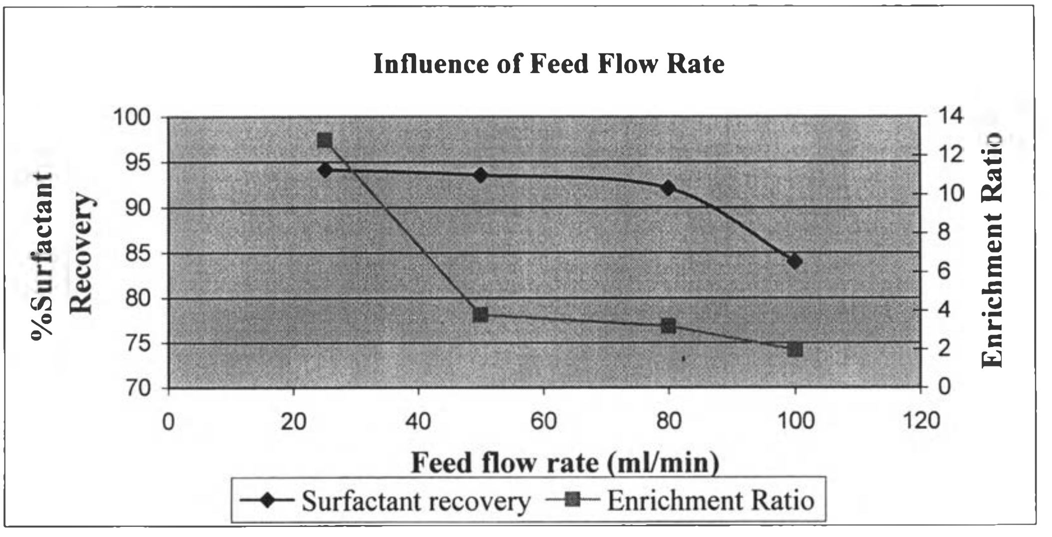
Conditions: [CPC] = 0.75 CMC; Air flow rate = 60 L/min; Feed flow rate = 50 ml/min; tray spacing =15 cm and No. of tray =5

Figure 4.16 (a) The effect of foam height on surfactant recovery and enrichment ratio and at [CPC] = 0.75 CMC.



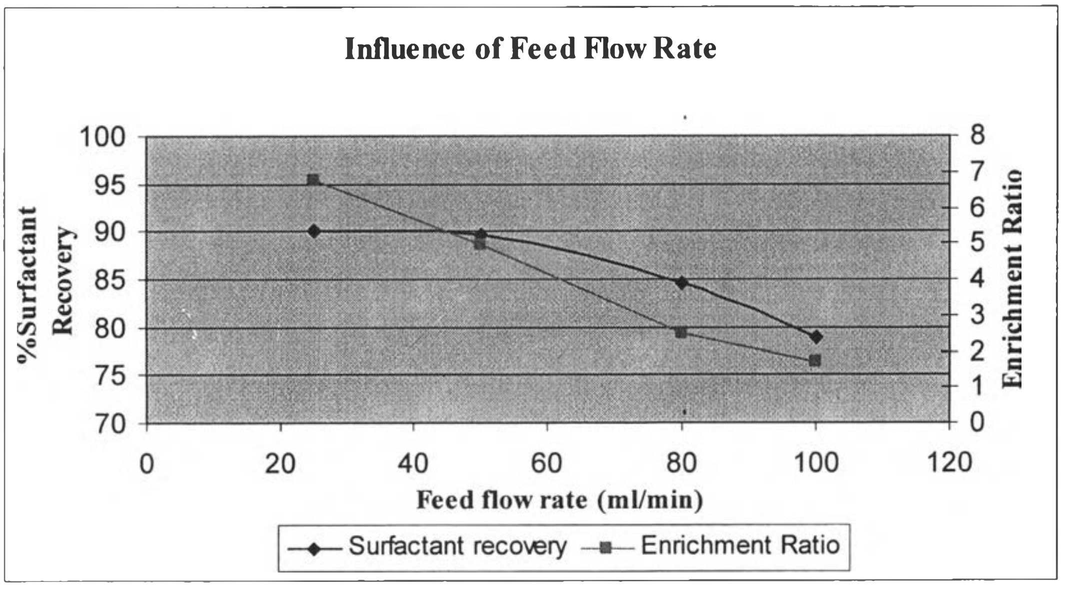
Conditions: [CPC] = 0.75 CMC; Air flow rate = 60 L/min; Feed flow rate = 50 ml/min; tray spacing =30 cm and No. of tray =5

Figure 4.16 (b) The effect of foam height on surfactant recovery and enrichment ratio and at [CPC] = 0.75 CMC.



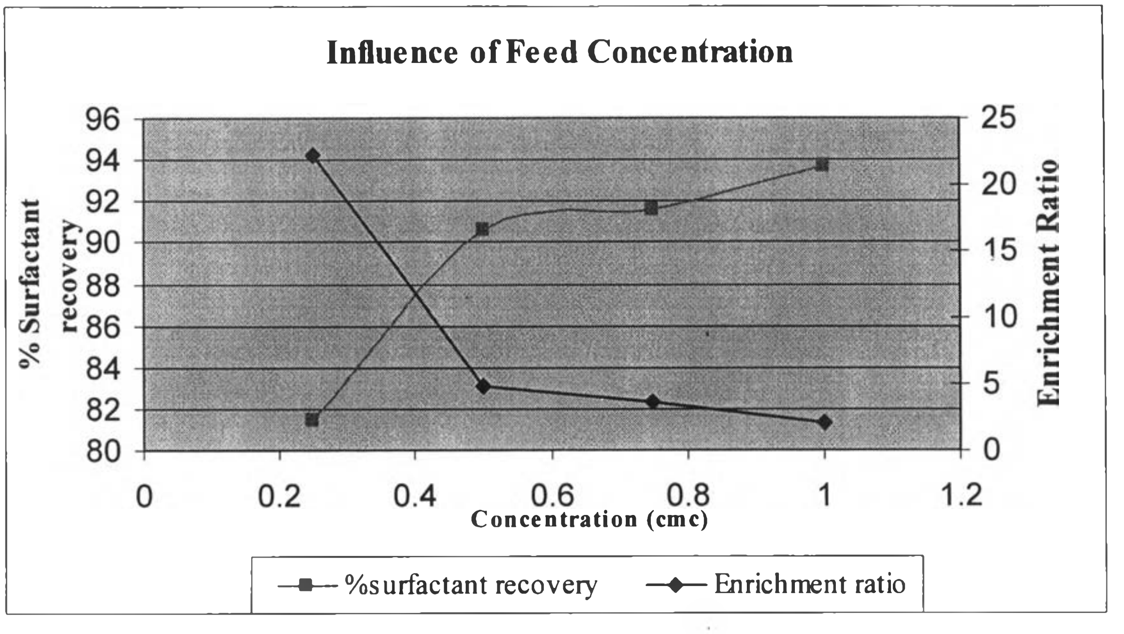
Condition: [CPC] = 0.75 CMC; Air flow rate = 40 L/min; foam height = 60 cm; tray spacing = 15 cm and No. of tray = 5

Figure 4.17 (a) The effect of liquid feed flow rate under the base case conditions and at [CPC] = 0.75 CMC.



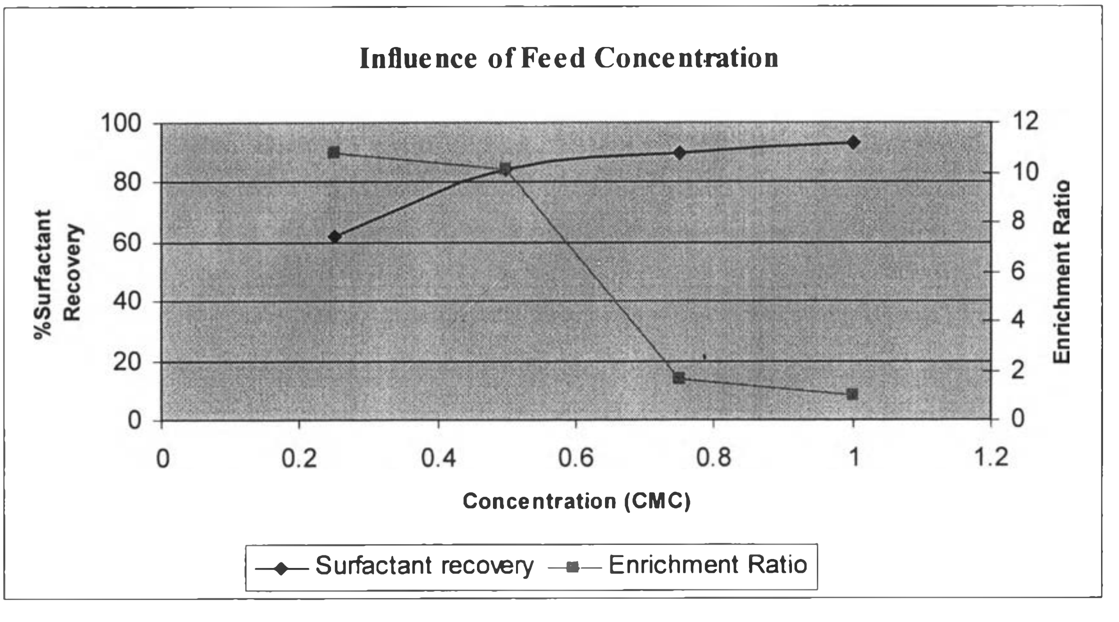
Condition: [CPC] = 0.75 CMC; Air flow rate = 40 L/min; foam height = 30 cm; tray spacing = 30 cm and No. of tray = 5

Figure 4.17 (b) The effect of liquid feed flow rate under the base case conditions and at [CPC] =0.75 CMC.



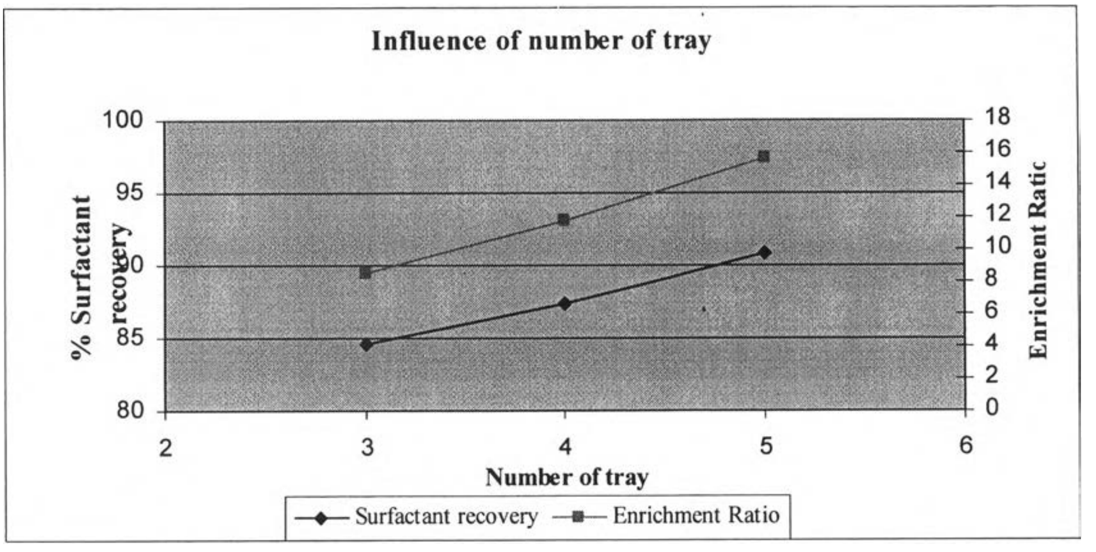
Condition: Air flow rate =40 L/min; Feed flow rate = 50 ml/min; foam height = 30 cm; tray spacing = 15 cm and No. of tray =5

Figure 4.18 (a) Influence of influent concentration.



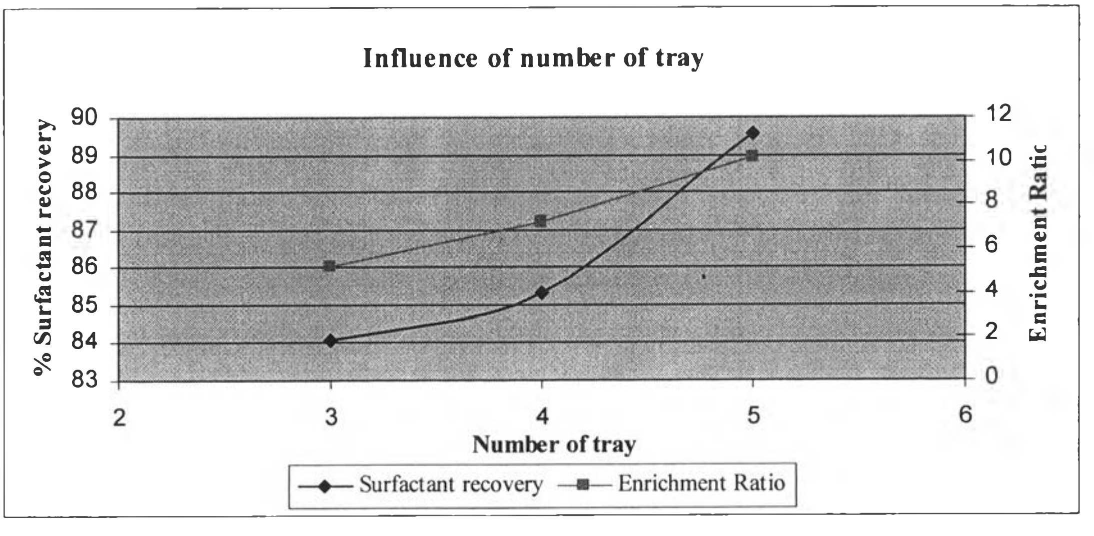
Condition: Air flow rate =50 L/min; Feed flow rate = 50 ml/min; foam height = 60 cm; tray spacing = 30 cm and No. of tray =3

Figure 4.18 (b) Influence of influent concentrations.



Condition: [CPC] = 0.5 CMC; Air flow rate =40 L/min; Feed flow rate = 50 ml/min; foam height = 60 cm; and tray spacing = 15 cm

Figure 4.19 (a) Influence of Number of tray.



Condition: [CPC] = 0.5 CMC; Air flow rate =40 L/min; Feed flow rate = 50 ml/min; foam height = 30 cm; and tray spacing = 30 cm

Figure 4.19 (b) Influence of Number of tray.