CHAPTER IV
RESULTS AND DISCUSSION

4.1 Steady-State Operation

The multi-stage foam fractionation unit used in this study was operated under steady state conditions. Steady state was insured when all measured parameters were invariant with time. From the concentration profiles shown in Figure 4.1, it takes about 6 hours for the system to reach steady state. Consequently, all experiments were carried out for a minimum of 6 hours before the samples were taken. All experimental data are given in Appendix A.

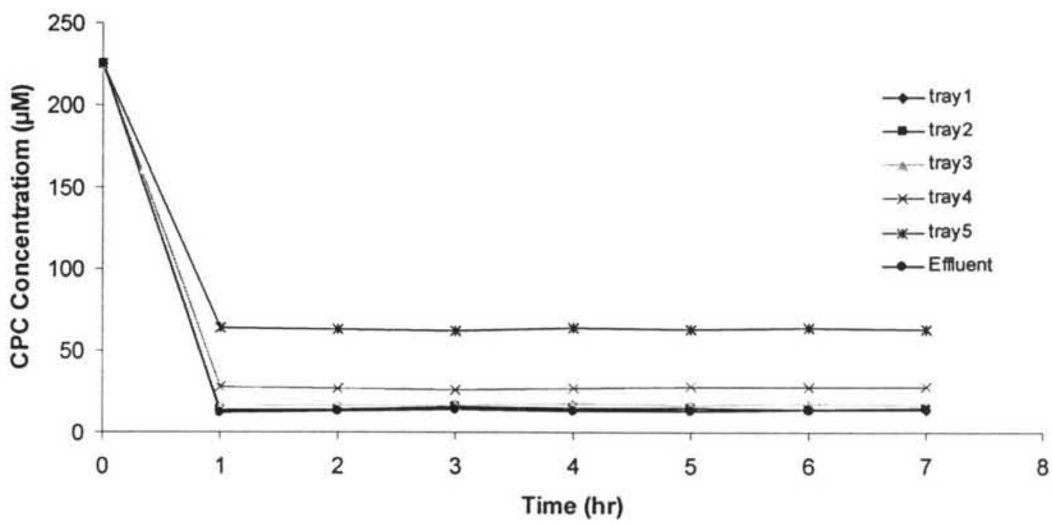

Figure 4.1 Concentration profiles with respect to time under operational condition of [CPC] = 0.225 mM; feed tray number 5; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

4.2 Operating Limits

The operating limits of the multi-stage foam fractionator were determined by varying both air and feed flow rates. Two important operational constraints; foam formation and flooding, are considered as the limits of the operation of foam fractionation. For the foam production; a sufficient air flow rate is needed to produce foam which can reach the foam outlet at the top stage when the very air flow but the liquid flow rate is not high enough to maintain sufficient liquid retention, the tray is completely filled with vapor leads to the foam production can not occurs. On the other hand, flooding is occurred when the liquid flow rate is too high the trays fill up completely with liquid. Figure 4.2 shows the boundary of the operational region of the foam fractionator used in this experiment. The maximum and minimum values of both air flow rate and liquid flow rate were used to run all experiments in order to avoid both flooding and no foam formation.

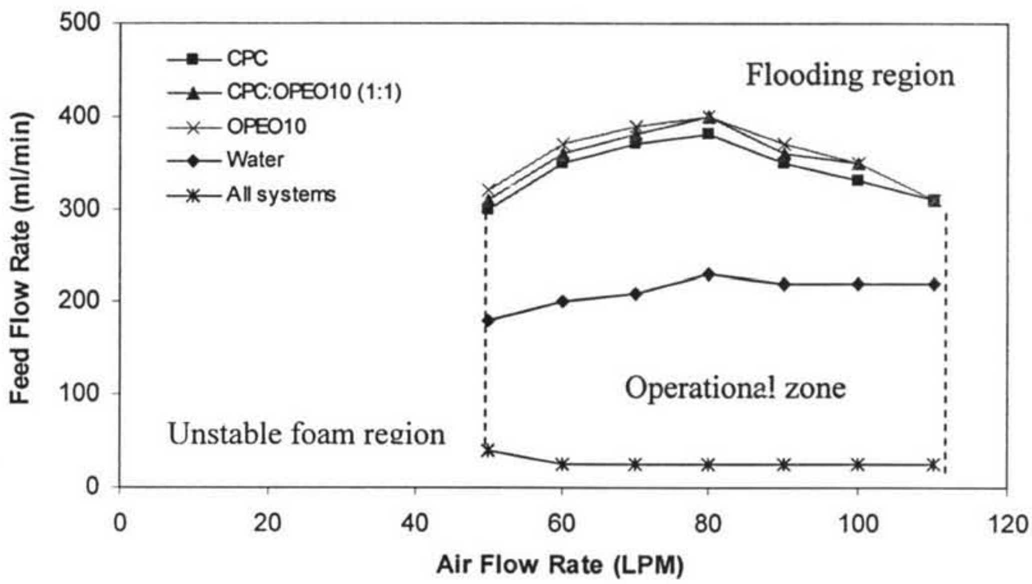

Figure 4.2 Operational zone under operational condition [sufactant] = 0.225 mM; foam height = 60 cm and feed tray number 5.

4.3 Foam characteristics of Single and Mixed Surfactant Systems

Foam characteristics in terms of stability and foam ability of single-surfactant and mixed-surfactant systems are shown in Figures 4.3 and Figure 4.4, respectively. In comparison CPC, $OPEO_{10}$ and mixed system, the foam stability of pure CPC system is higher than that of pure $OPEO_{10}$ as shown in Figure 4.4. It can be explained that the repulsive force between the layers of lamellae of the foam produced from pure CPC system is greater than that produced from pure $OPEO_{10}$ system because the repulsive force between the head groups of CPC is greater than those of $OPEO_{10}$. An increase in the surfactant concentration causes an increase both the foam ability and the foam stability as shown in Figure 4.3 and Figure 4.4. Due to increase the surfactant concentration not only reduce surface tension but also increase the viscosity resulted in the foam can occur easily and the liquid drainage from the foam lamella is decreased. As can be seen from Figure 4.4, the foam stability of mixed surfactant systems is higher than those of both single surfactant systems of CPC and $OPEO_{10}$. This is because an addition of $OPEO_{10}$, nonionic surfactant can reduce the repulsive force between the positive head groups of CPC resulting in having more CPC molecules adsorbing on both surface of the lamellae. As a result, the foam stability increases.

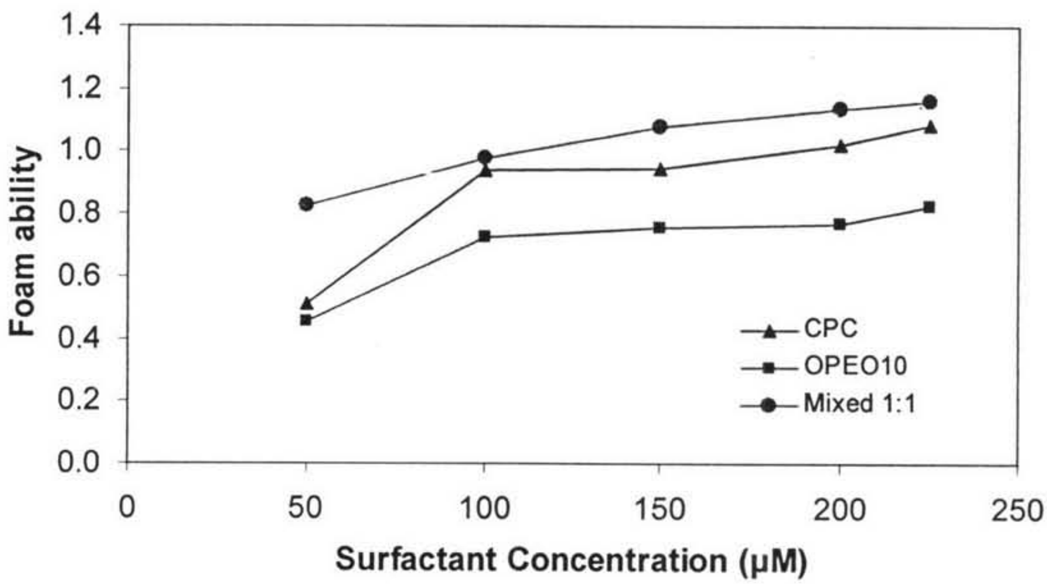

Figure 4.3 Foam ability of various surfactant systems operated at air flow rate = 0.1 L/min and surfactant solution = 250 ml.

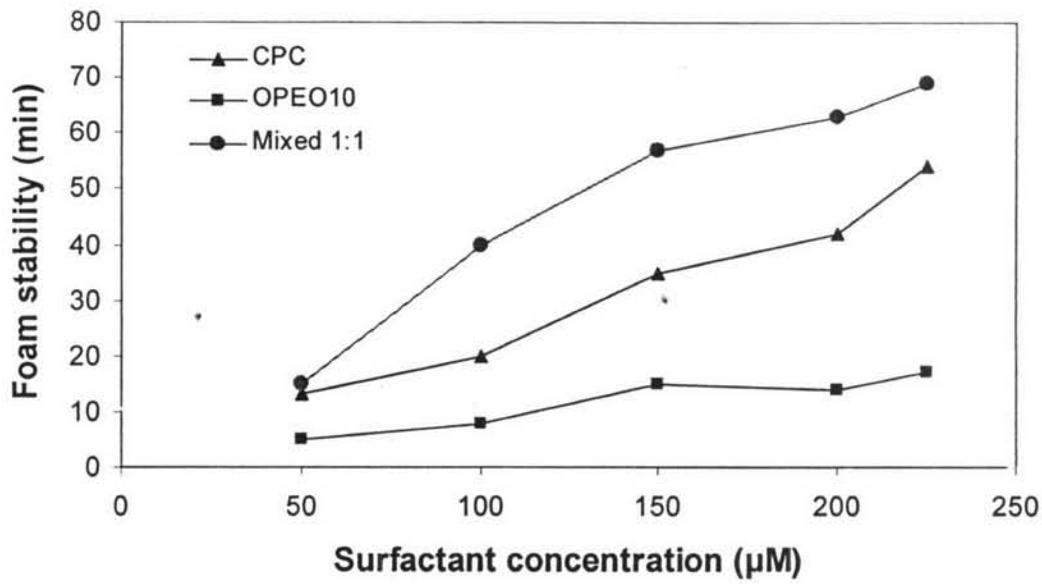

Figure 4.4 Foam stability of various types of surfactant solutions air flow rate = 0.1 L/min and surfactant solution = 250 ml.

4.3 Apparent Diffusion Coefficient of Surfactants (D_{ap})

The Surfactant that have large diffusion coefficient (D_{ap}), meaning faster diffusion of these molecules to the gas/liquid interface. To calculate the value of D_{ap} at short time based on the short-time approximation equation of Ward and Tordai, and using dynamic short-time surface tension data, may be used:

$$\frac{(\gamma_0 - \gamma_t)}{C} = 2RT\left(\frac{D_{ap}}{\pi}\right)^{1/2} t^{1/2} \tag{4.1}$$

At constant surfactant concentration, C, in the solution, a plot of $(\gamma_0 - \gamma_t)$ versus $t^{1/2}$ should be linear, if adsorption is diffusion controlled (generally true, for simple structure surfactants) and permits evaluate of D_{ap} from the slope of the plot.

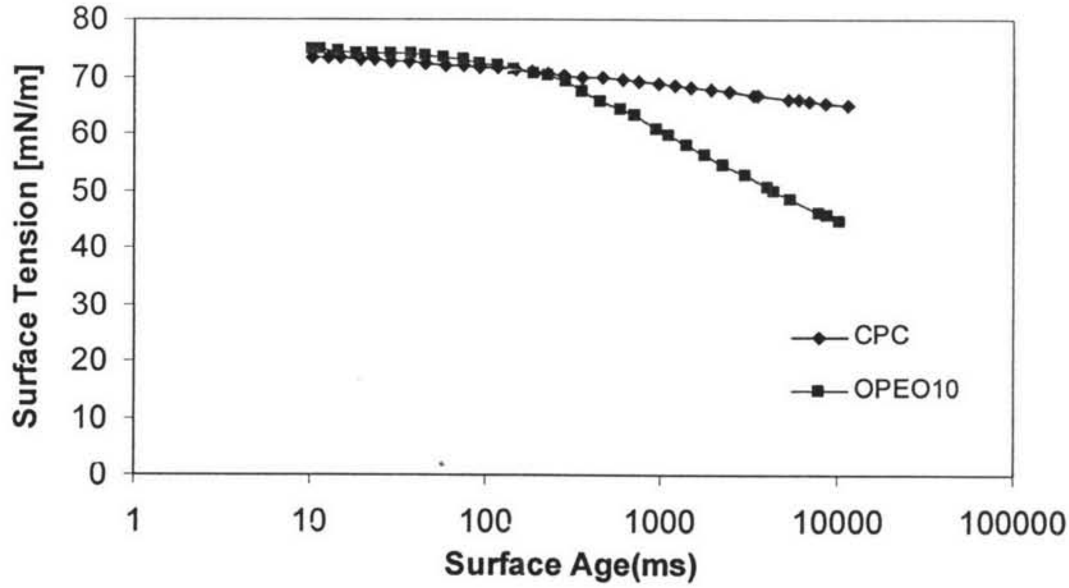

Figure 4.5 The dynamic surface tension of surfactants.

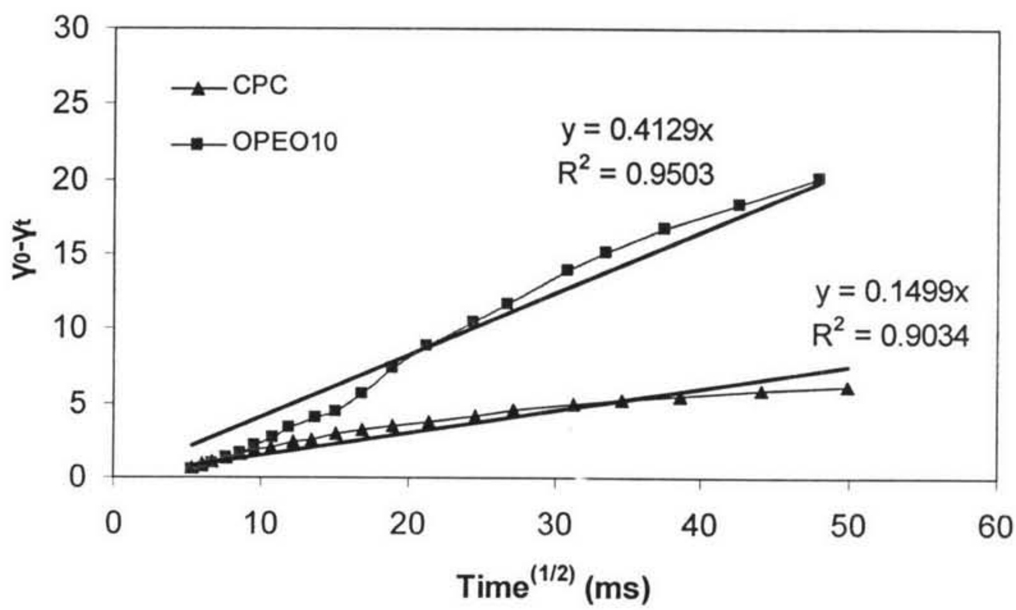

Figure 4.6 $(\gamma_0\text{-}\gamma_t)$ versus $t^{(1/2)}$.

Table 4.1 The apparent diffusion coefficients

Surfactants	D_{ap} (m^2/ms)
CPC	0.1499
$OPEO_{10}$	0.4129

4.5 Multi-stage Foam Fractionator Efficiencies of Single-surfactant Systems

The experimental data taken after the steady state established were analyzed to determine the effects of process parameters affecting the recovery of CPC and $OPEO_{10}$. Efficiencies of the surfactant separation were evaluated in terms of the %surfactant recovery and the enrichment ratio was as defined in the previous chapter.

4.5.1 Effect of Feed Position

Figure 4.7 and Figure 4.8 show the effect of the feed position on the separation efficiencies of two pure surfactants of CPC and $OPEO_{10}$. Figure 4.7 shows the %surfactant recovery of the pure CPC system increases when the feed position was increased and reached the maximum value at tray number 3 after that the %surfactant recovery started to decrease, the enrichment ratio shows the opposite result to %surfactant recovery while the %surfactant recovery of the pure $OPEO_{10}$ system increases with increasing the feed position but the enrichment ratio decreases until constant as shown in Figure 4.8. Figure 4.11 and Figure 4.12 show the concentration profile of two pure surfactant systems, the highest surfactant concentration observed at the tray that the solution was fed. The highest surfactant concentration decreased when the feed position was changed from tray number 5 to tray number 4, 3, 2 and 1, respectively. The possible reason is that the liquid from the upper tray over the feed tray reduces the surfactant concentration of the feed tray. Therefore, the lower feed position tray, the lower in the highest surfactant concentration. The foam production rate of CPC is much higher than that of $OPEO_{10}$ tend to produce wetter foam because of more bubbles generated to lower the liquid drainage rate resulting in lowering the enrichment ratio as shown in Figure 4.9 and Figure 4.10. Figure 4.13 shows the comparison of surfactant separation performance between pure CPC and pure $OPEO_{10}$ systems. In comparison, the enrichment ratio of $OPEO_{10}$ in the rang of 130-160 was higher than the enrichment ratio of CPC in the rang of 1-6. This is because the foam stability of $OPEO_{10}$ is much lower than that of CPC, it means that in the case of $OPEO_{10}$ system the liquid in the foam lamella could drainage faster results in have much higher the enrichment ratio as compare to CPC system. Interestingly, when compared the separation efficiencies of CPC and $OPEO_{10}$ obtained from the present study to those of the previous work, it shows the effect of feed position in the previous work could not observe. This is because the present foam fractionation has contained more bubble caps (22 caps per tray) than the previous unit (8 caps per tray). An increase in the number of bubble caps increase the gas/liquid interfacial area leading to an increase in the mass transfer of surfactant.

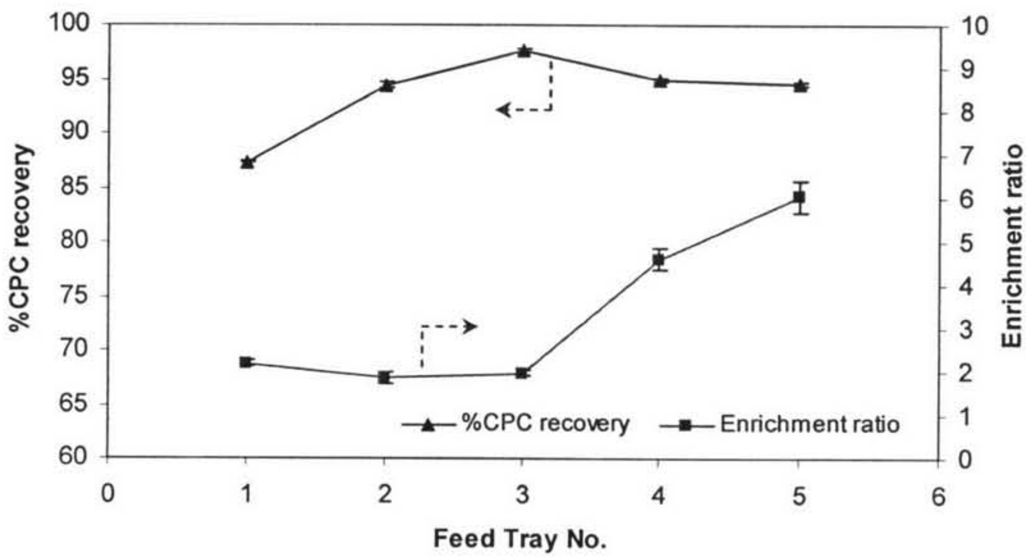

Figure 4.7 Effect of Feed Position under operational condition of [CPC] = 0.225 mM; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

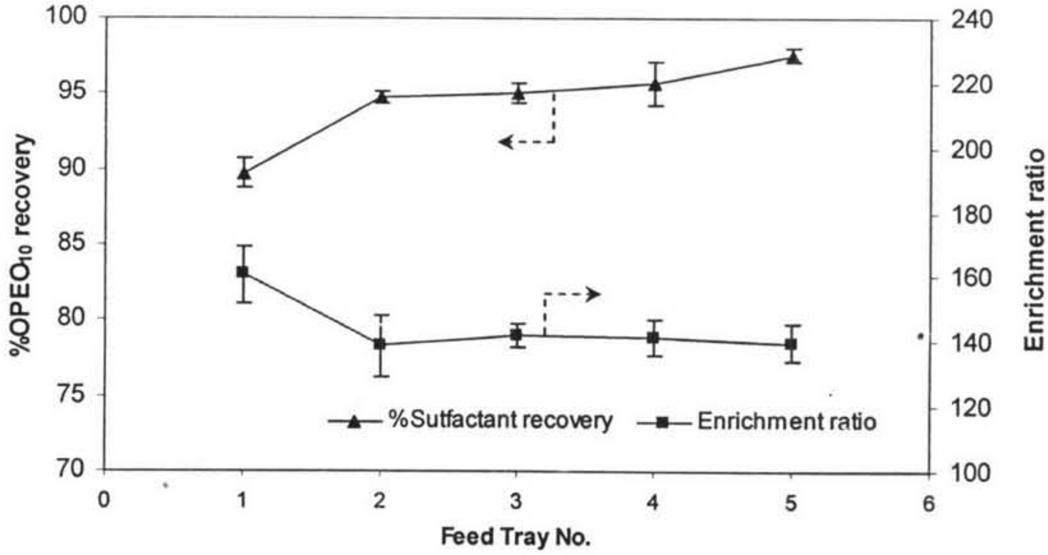

Figure 4.8 Effect of Feed Position under operational condition of [$OPEO_{10}$] = 0.225 mM; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

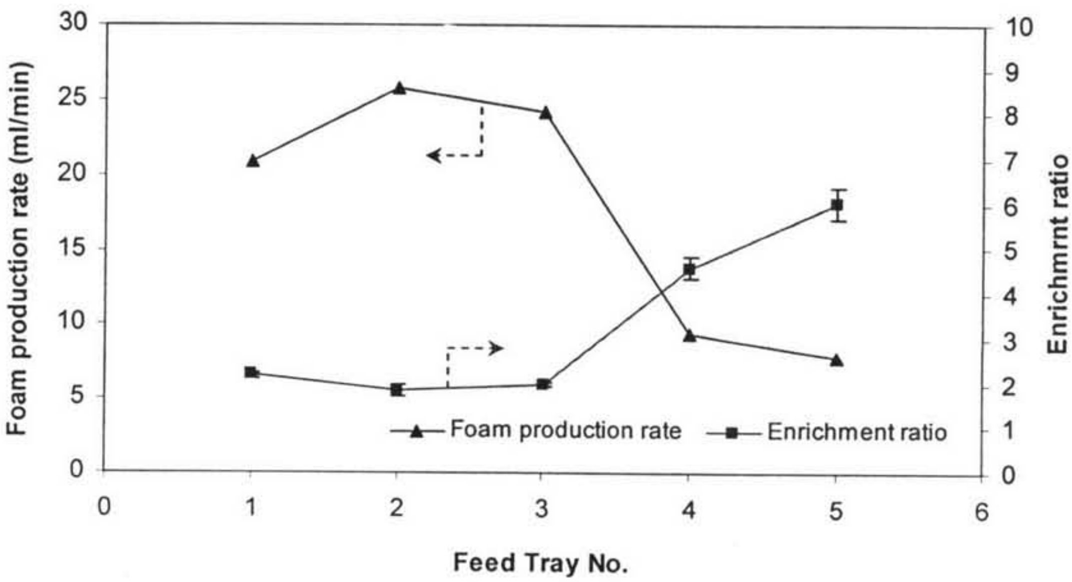

Figure 4.9 Relations between foam production rate and enrichment ratio under operational condition of [CPC] = 0.225 mM; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

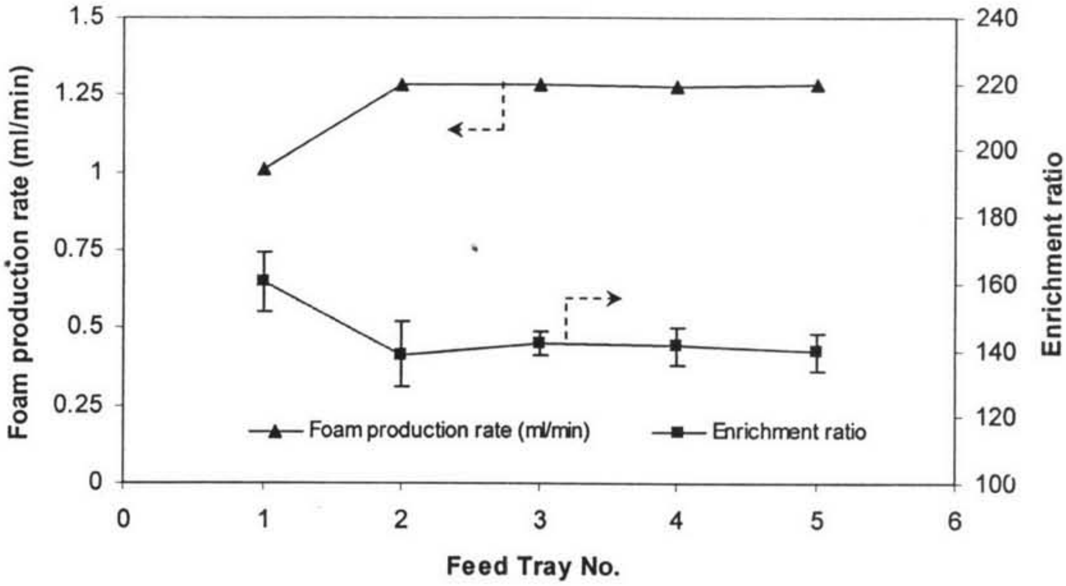

Figure 4.10 Relations between foam production rate and enrichment ratio under operational condition of $[OPEO_{10}]$ = 0.225 mM; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

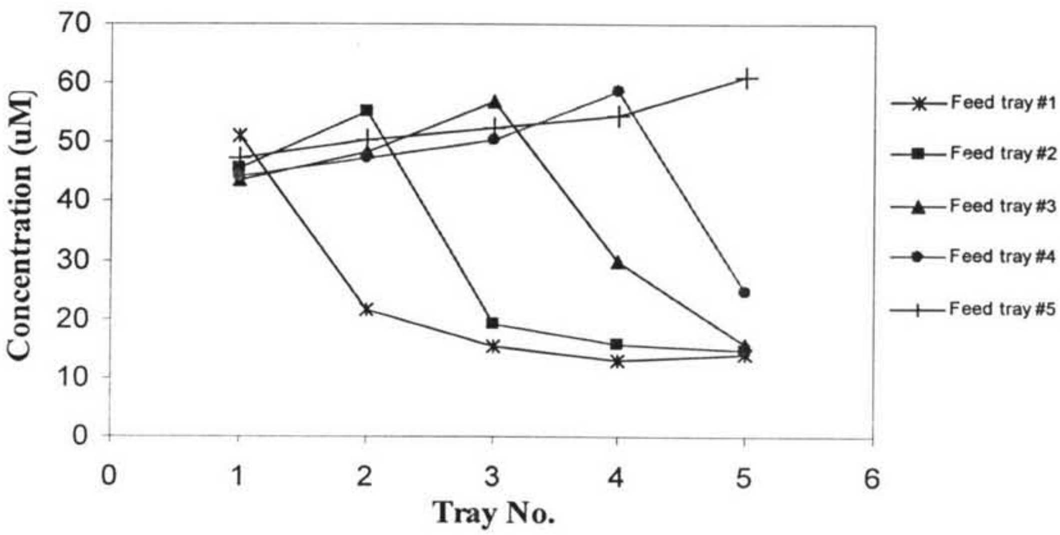

Figure 4.11 The concentration profile of CPC when vary feed position under operational condition of [CPC] = 0.225 mM; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

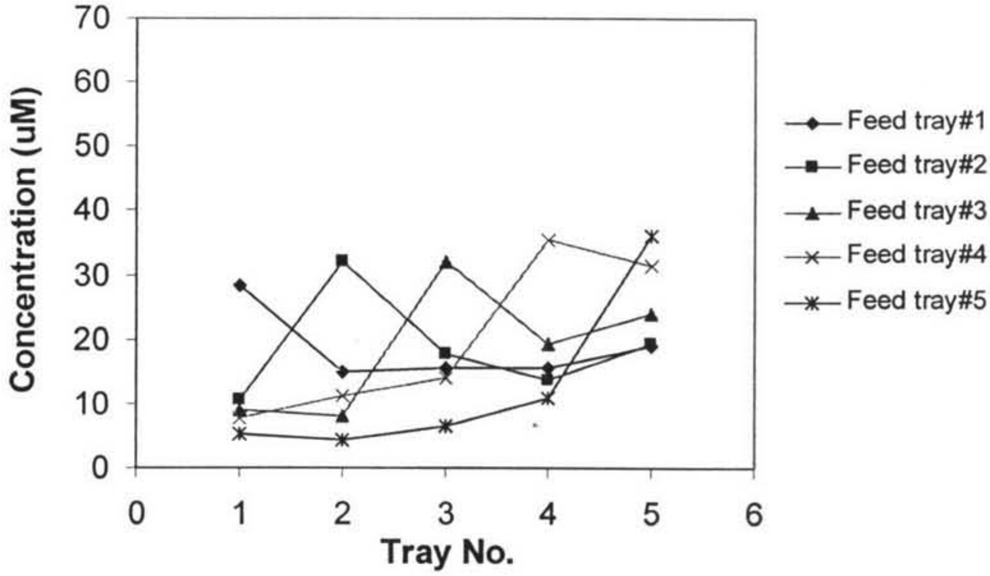

Figure 4.12 The concentration profile of $OPEO_{10}$ when vary feed position under operational condition of [$OPEO_{10}$] = 0.225 mM; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

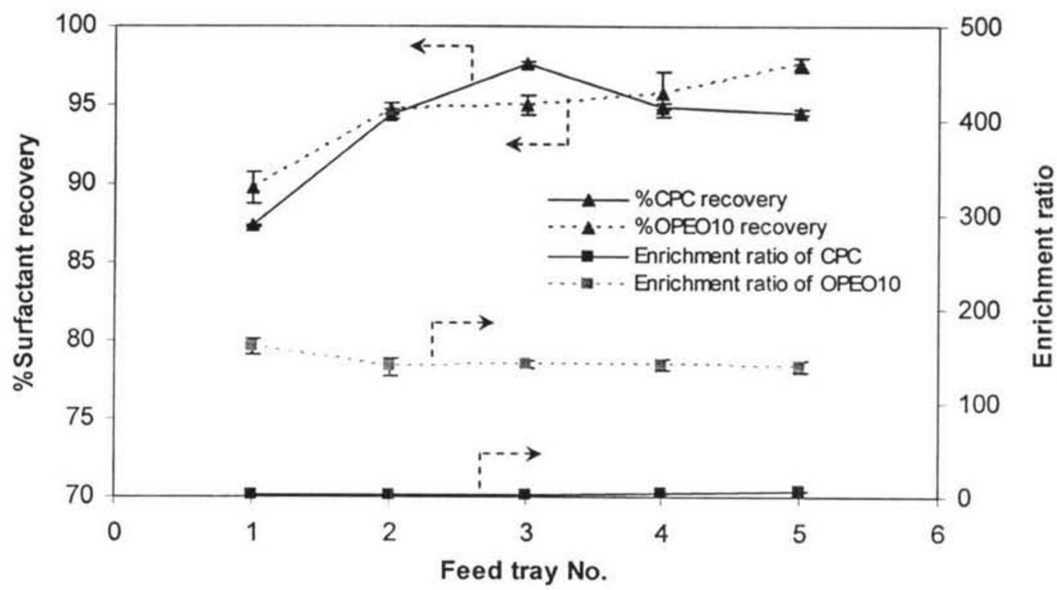

Figure 4.13 Comparison of the surfactant recovery between pure CPC and $OPEO_{10}$ systems under operational condition of [surfactant] = 0.225 mM; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

4.5.2 Effect of Reflux Position

The effect of the reflux position on the separation efficiencies of pure CPC and $OPEO_{10}$ systems are shown in Figures 4.14 and 4.15, respectively. An increase in the reflux position was not significant in both the %surfactant recovery and the enrichment ratio. The %surfactant recovery in the non-reflux system was higher than the system that has the reflux stream. The possible reason is that the reflux stream has the low surfactant concentration added to the system resulting in a decrease in the total surfactant concentration of the system. Therefore, the foam ability of the system was decreased. From Figure 4.20, it can be seen that the effectiveness of foam fractionation process in the enrichment ratio of $OPEO_{10}$ is better than for CPC that can be explained by the diffusion coefficient and foam stability for the same reason discussed in the previous section. Figures 4.16 and 4.17 show the relation between the foam production rate and the enrichment ratio of both pure surfactant systems. Although the both systems have the reflux stream but the concentration profile has remained the same trend with the non-reflux system as shown in Figure 4.18 and Figure 4.19.

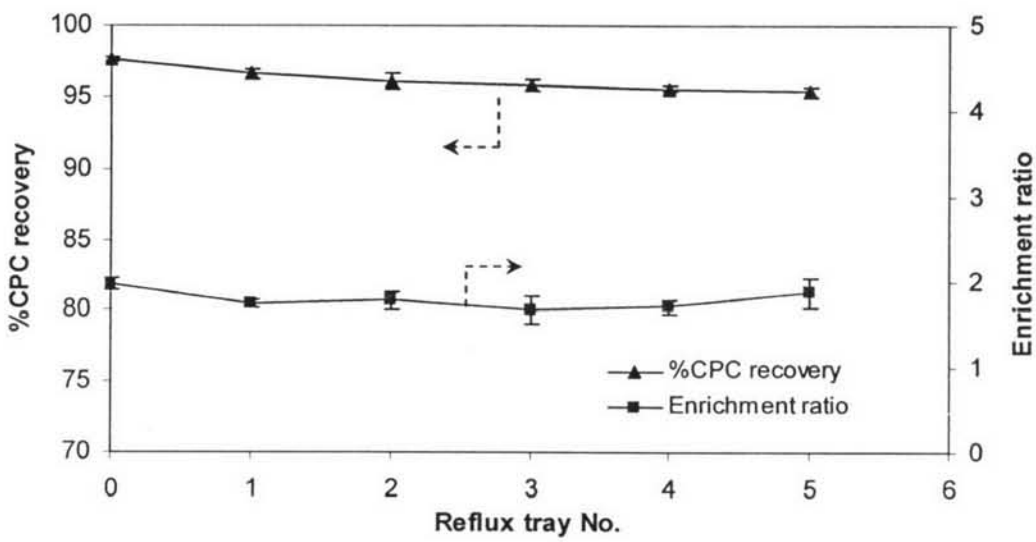

Figure 4.14 Effect of reflux position under operational condition of [CPC] = 0.225 mM; feed position = tray number 3; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

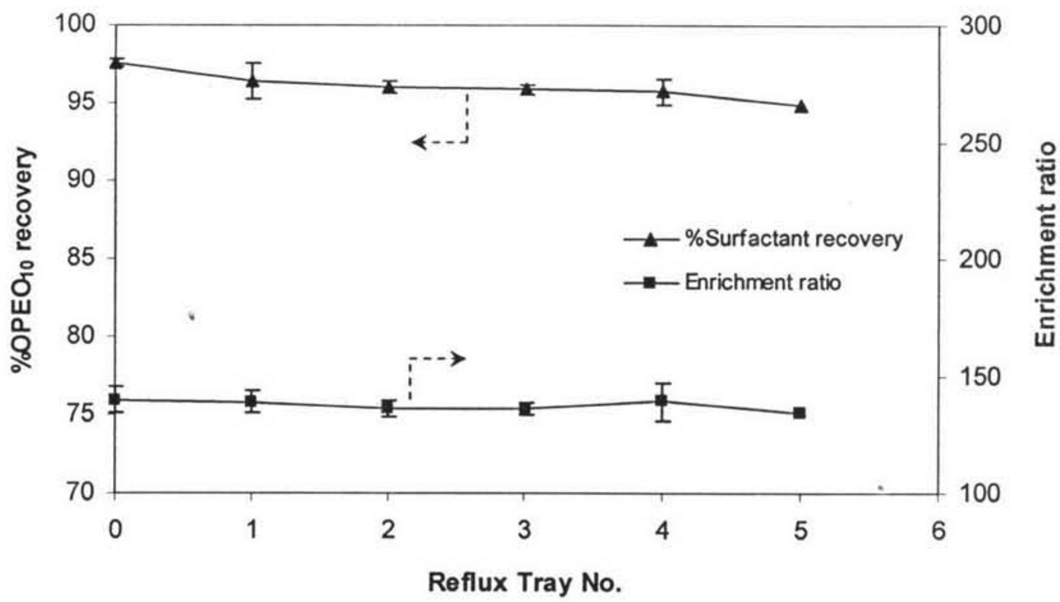

Figure 4.15 Effect of Reflux Position under operational condition of $[OPEO_{10}]$ = 0.225 mM; feed position = tray number 5; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

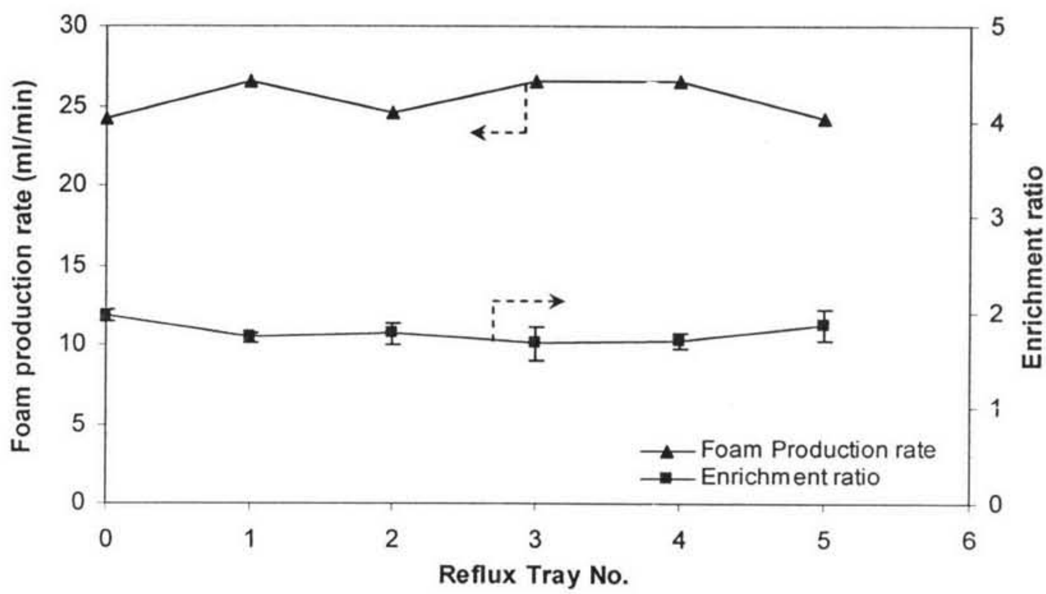

Figure 4.16 Relations between foam production rate and enrichment ratio under operational condition of [CPC] = 0.225 mM; feed position = tray number 3; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

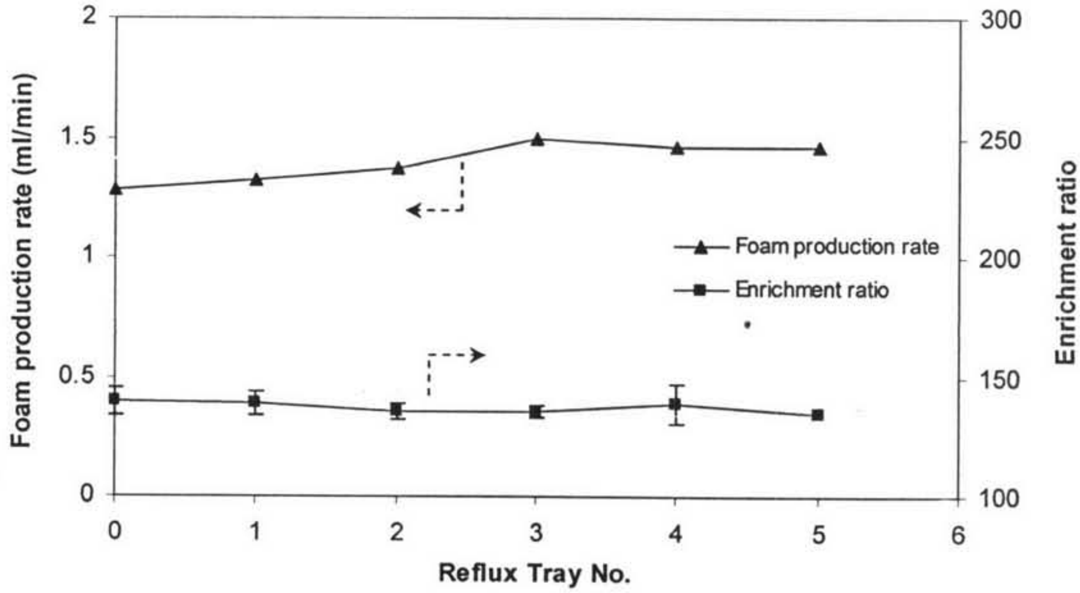

Figure 4.17 Relations between foam production rate and enrichment ratio under operational condition of [$OPEO_{10}$] = 0.225 mM; feed position = tray number 5; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

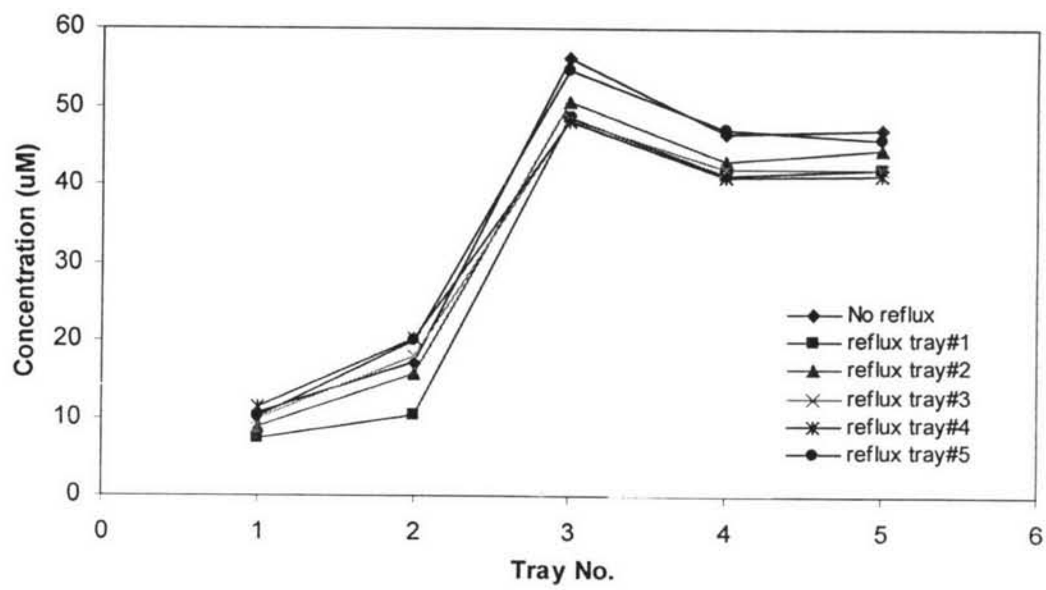

Figure 4.18 The concentration profile of CPC when vary reflux position under operational condition of [CPC] = 0.225 mM; feed position = tray number 3; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

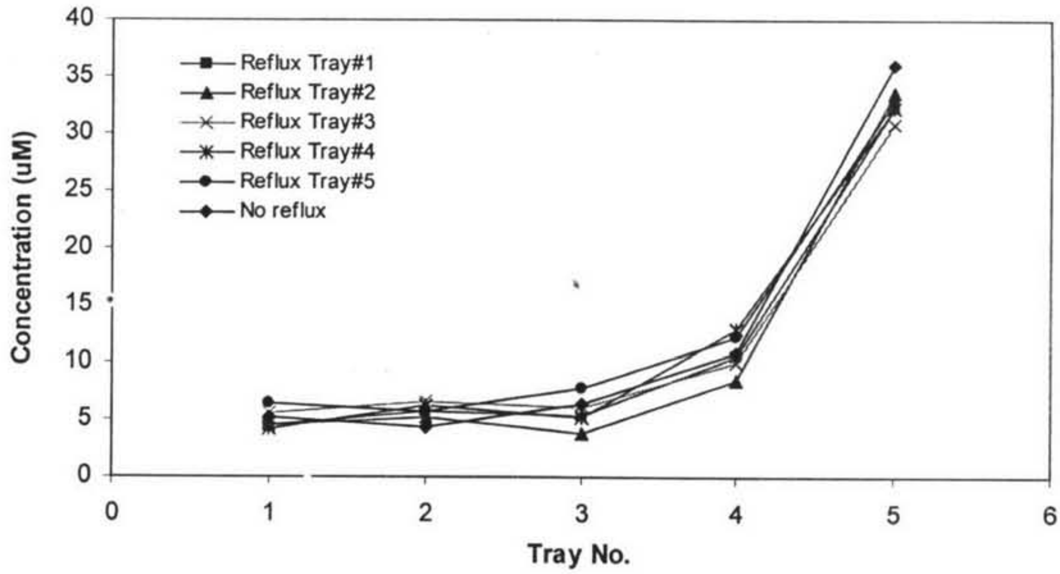

Figure 4.19 The concentration profile of $OPEO_{10}$ when vary reflux position under operational condition of $[OPEO_{10}]$ = 0.225 mM; feed position = tray number 5; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

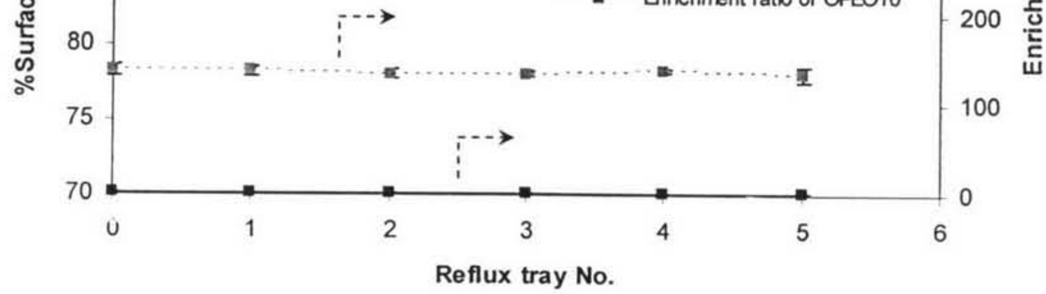

Figure 4.20 Comparison of the surfactant recovery between pure CPC and $OPEO_{10}$ system under operational condition of [surfactant] = 0.225 mM; feed position of CPC = tray number 3; feed position of $OPEO_{10}$ = tray number 5; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

4.5.3 Effect of Reflux Ratio

The effect of the reflux ratio was studied by varying from 0.25 to 1. Figures 4.21 and 4.22 illustrate the influence of the reflux ratio on the surfactant separation efficiencies of pure CPC and $OPEO_{10}$, respectively. From Figures 4.21 and 4.22, an increase in the reflux ratio resulted in decreasing the %CPC recovery while not effecting on the $OPEO_{10}$ system and the effect of reflux ratio on the enrichment ratio of both systems were not significant. For all conditions, the %surfactant recovery of CPC was in the range of 90-98%. A cause of a decrease in the %CPC recovery when increasing the reflux ratio due to the CPC system could not recover the surfactant in the solution before it will drain from the column because the diffusion coefficient of CPC was lower than $OPEO_{10}$. Figur e 4.27 sh ows a comparison of the surfactant separation efficiencies between CPC and $OPEO_{10}$ systems. Although the reflux ratio was increased but the concentration profile of all conditions could observe the same trend as shown in Figures 4.25 and 4.26.

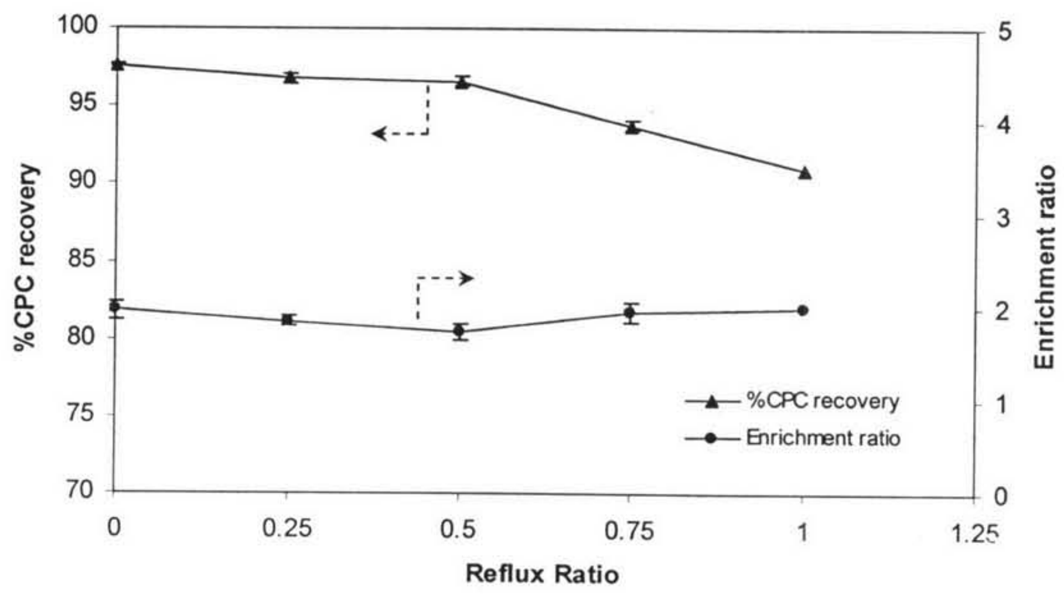

Figure 4.21 Effect of Reflux Ratio under operational condition of [CPC] = 0.225 mM; feed position = tray number 3; reflux position = tray number 1; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

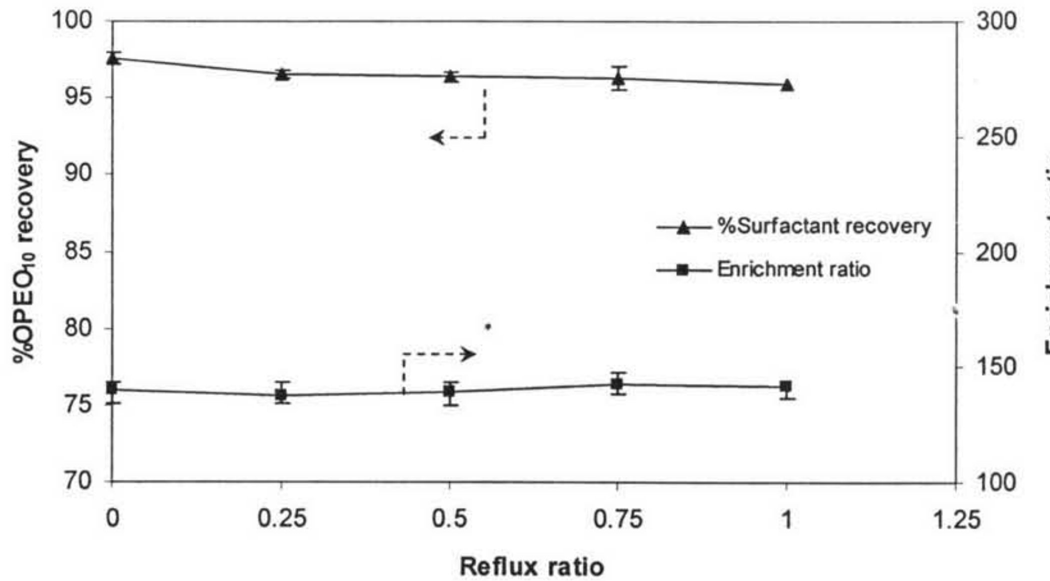

Figure 4.22 Effect of Reflux Ratio under operational condition of [$OPEO_{10}$] = 0.225 mM; feed position = tray number 5; reflux position = tray number 1; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

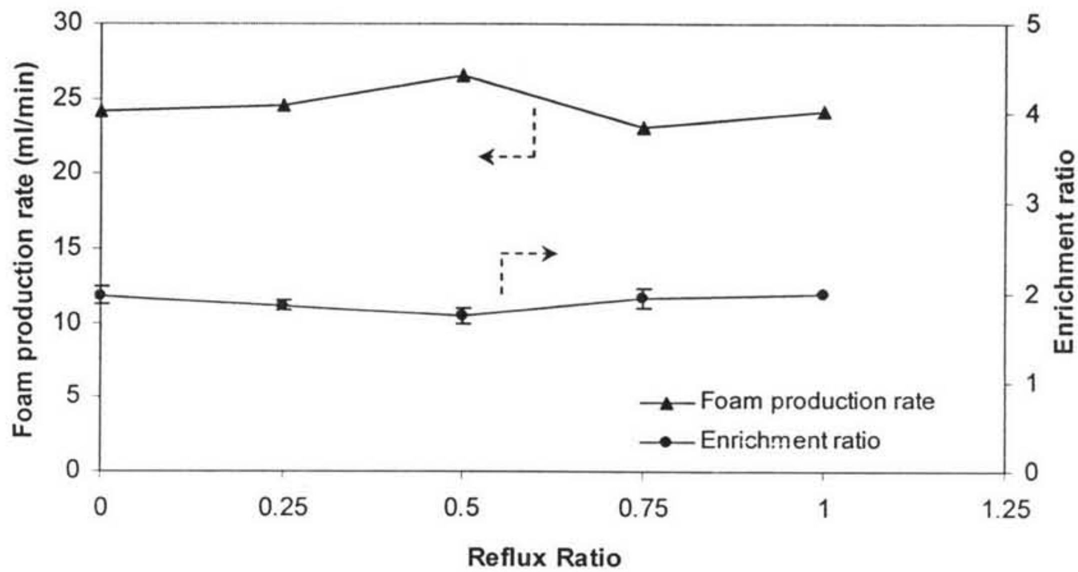

Figure 4.23 Relations between foam production rate and enrichment ratio under operational condition of [CPC] = 0.225 mM; feed position = tray number 3; reflux position = tray number 1; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

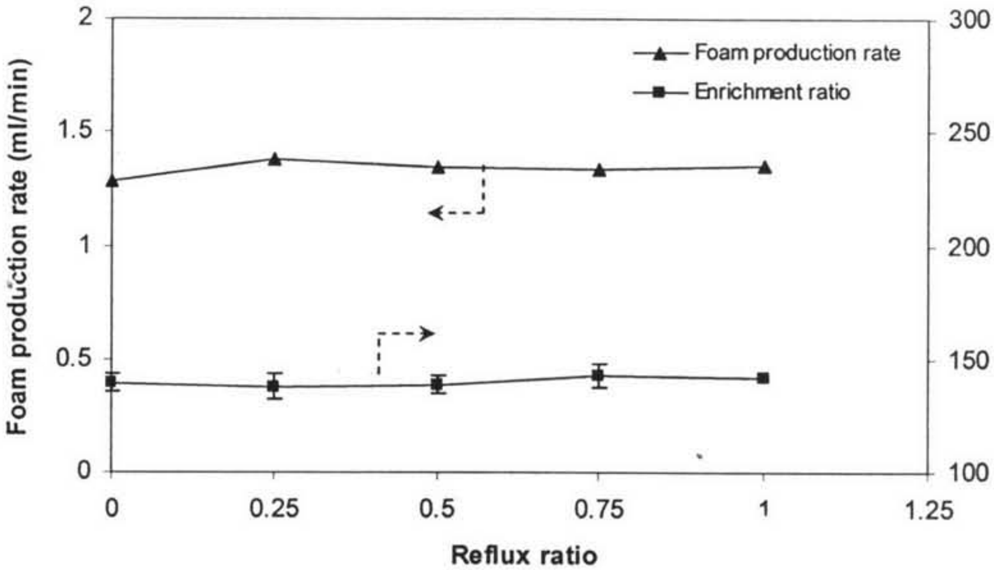

Figure 4.24 Relations between foam production rate and enrichment ratio under operational condition of [$OPEO_{10}$] = 0.225 mM; feed position = tray number 5; reflux position = tray number 1; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

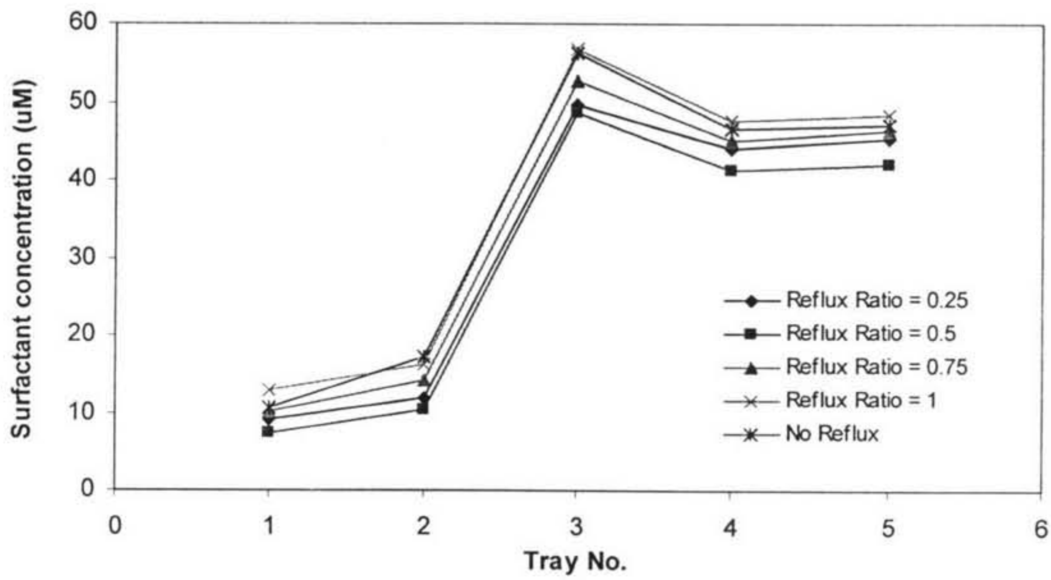

Figure 4.25 The concentration profile of CPC when vary reflux position under operational condition of [CPC] = 0.225 mM; feed position = tray number 3; reflux position = tray number 1; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

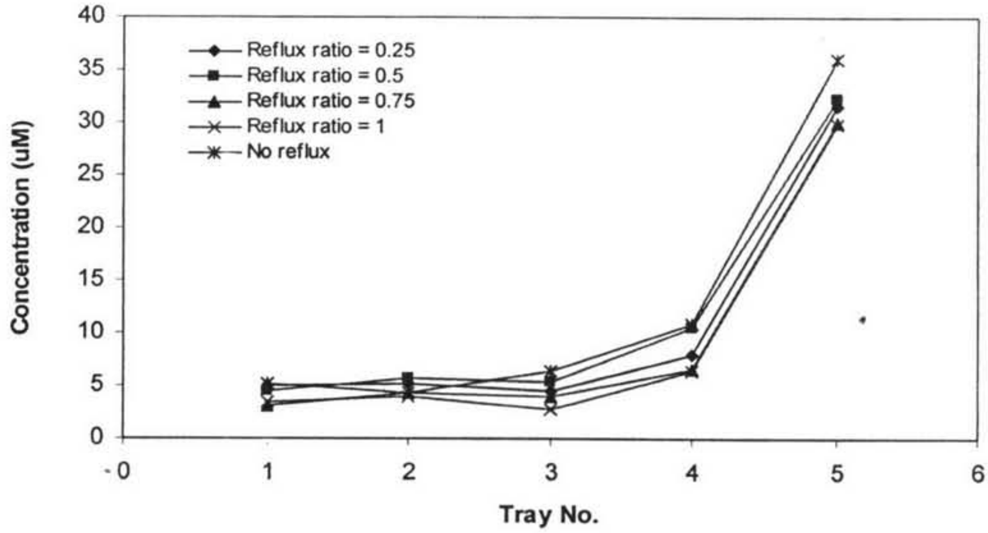

Figure 4.26 The concentration profile of CPC when vary reflux position under operational condition of $[OPEO_{10}]$ = 0.225 mM; feed position = tray number 5; reflux position = tray number 1; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

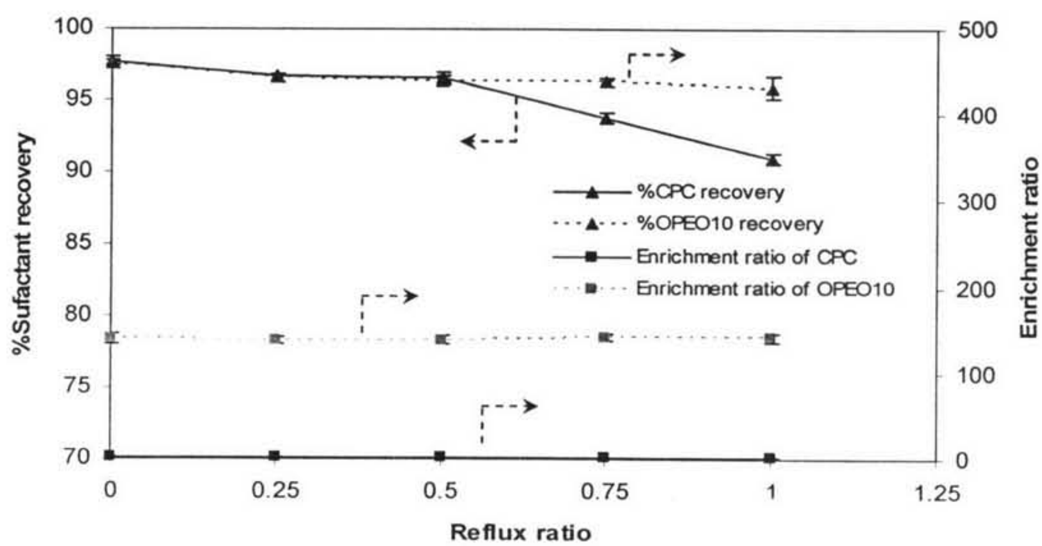

Figure 4.27 Comparison of the surfactant recovery between pure CPC and $OPEO_{10}$ system under operational condition of [surfactant] = 0.225 mM; feed position of CPC = tray number 3; feed position of $OPEO_{10}$ = tray number 5; reflux position = tray number 1; feed flow rate = 50 ml/min; air flow rate = 80 L/min and foam height = 60 cm.

4.6 Multi-stage Foam Fractionator Efficiencies of Mixed Surfactant Systems

In this part of the study, the effects of various parameters such as feed position, reflux position and reflux ratio on the separation efficiencies of CPC and $OPEO_{10}$ were studied in a continuous mode of the multi-stage fractionator at total surfactant concentration 0.225 mM, 5 trays, feed flow rate at 50 ml/min, air flow rate at 80 L/min and foam height at 60 cm. In the mixed CPC to $OPEO_{10}$ as 1:1 system, the separation efficiencies are presented in terms of the %surfactant recoveries and the enrichment ratios of each surfactant as given below:

$$\% \text{ Surfactant recovery} = \frac{(C_{i,n}F_{i,n} - C_{e,n}F_{e,n})}{C_{i,n}F_{i,n}} * 100 \qquad (4.2)$$

$$\text{Enrichment ratio} = \frac{C_{f,n}}{C_{i,n}} \qquad (4.3)$$

where C_i is the surfactant concentration in the influent stream (mM)

C_e is the surfactant concentration in the effluent stream (mM)

C_f is the surfactant concentration in the foam concentrated stream (mM)

F_i is the feed flow rate (ml/min)

F_e is the effluent flow rate (ml/min)

and subscript n refers to CPC or $OPEO_{10}$.

4.6.1 Effect of Feed Position

The effect of the feed position on the separation efficiencies of the mixed-surfactant system is shown in Figure 4.28 and Figure 4.29. From these figure, the same trend was observed that increasing the feed position resulted in an increase in both the %surfactant recovery and the enrichment ratio. For the mixed-surfactant system with any given the feed position, the values of the %surfactant recovery and the enrichment ratio of $OPEO_{10}$ were higher than those of CPC. Interestingly, the surfactant recovery of $OPEO_{10}$ in the mixed-surfactant system is enhanced by the presence of CPC in the system. The surfactant recovery of $OPEO_{10}$ is almost 100% as seen in Figure 4.28. The %$OPEO_{10}$ recovery in the mixed system is greater than that of CPC. This is because $OPEO_{10}$ has larger diffusion coefficient than CPC, it mean that $OPEO_{10}$ diffuse from the bulk solution to the gas/liquid interface faster than CPC. The values of the %surfactant recovery of pure CPC and $OPEO_{10}$ system are intermediate between those of CPC and $OPEO_{10}$ in the mixed-surfactant system. In contrast, the values of the enrichment ratio of CPC and $OPEO_{10}$ in the mixed-surfactant system are intermediate between those of pure CPC and $OPEO_{10}$ systems. Due to the foam stability of the mixed-surfactant system is higher than that of the pure $OPEO_{10}$ system as shown in Figure 4.4.

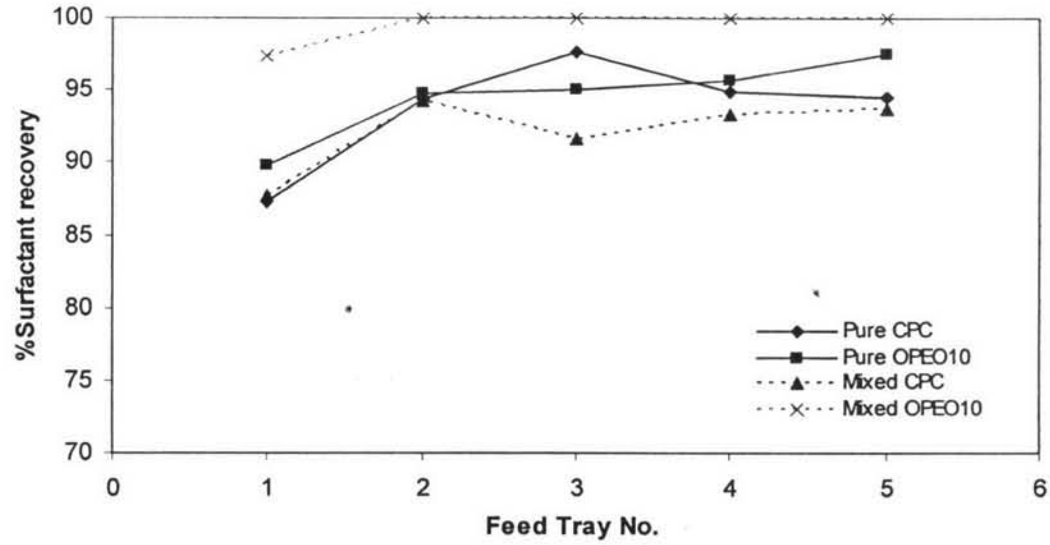

Figure 4.28 Effect of Feed Position on the %surfactant recovery of each surfactant of the mixed-surfactant system under operational condition of [total surfactant] = 0.225 mM; molar ratio of CPC to $OPEO_{10}$ = 1:1.

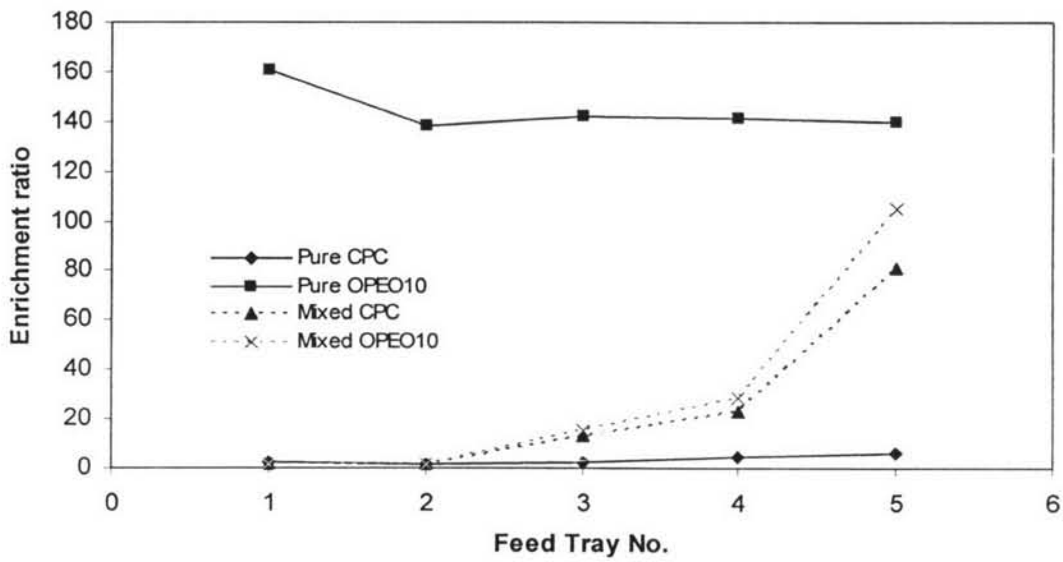

Figure 4.29 Effect of Feed Position on the enrichment ratio of each surfactant of the mixed-surfactant system under operational condition of [total surfactant] = 0.225 mM; molar ratio of CPC to $OPEO_{10}$ = 1:1.

4.6.2 Effect of Reflux Position

The effect of the reflux position on the separation efficiencies of each surfactant of the mixed-surfactant system are shown in Figure 4.30 and 4.31. When comparing the separation efficiencies of CPC and $OPEO_{10}$, it can be seen that for any given the reflux position, both the %surfactant recovery and the enrichment ratio of $OPEO_{10}$ were higher than those of CPC. According to these figures, both the enrichment ratio and the %surfactant recovery of CPC in mixed system were not changed as the reflux position increased but it was lower than that of the non-reflux system. The possible explanation is the same discussed in the single surfactant systems and the previous section. However, the values of the %surfactant recovery of pure CPC and $OPEO_{10}$ system are intermediate between those of CPC and $OPEO_{10}$ in the mixed-surfactant system.

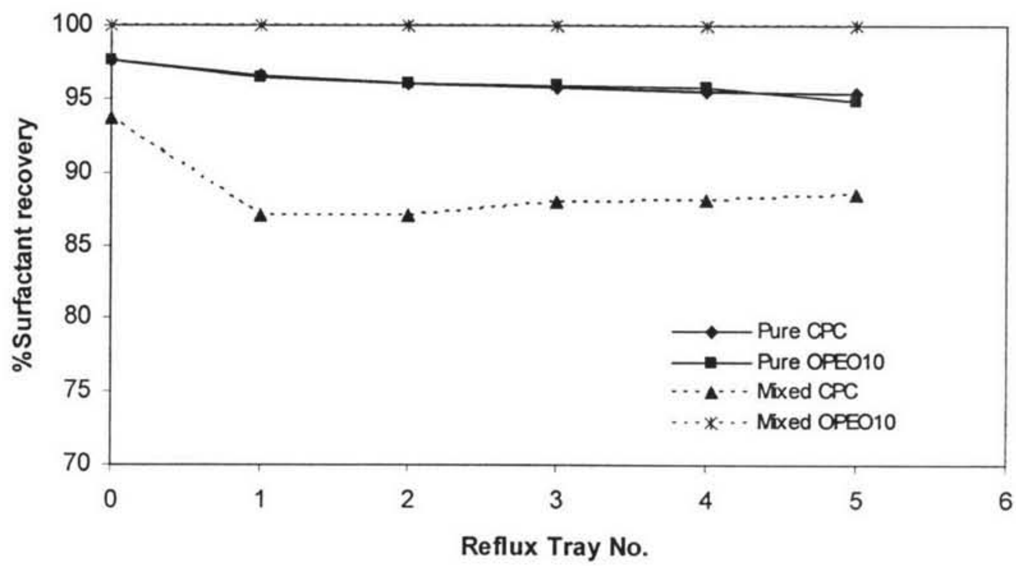

Figure 4.30 Effect of Reflux Position on the %surfactant recovery of each surfactant of the mixed-surfactant system under operational condition of [total surfactant] = 0.225 mM; molar ratio of CPC to $OPEO_{10}$ = 1:1; feed position = tray number 5.

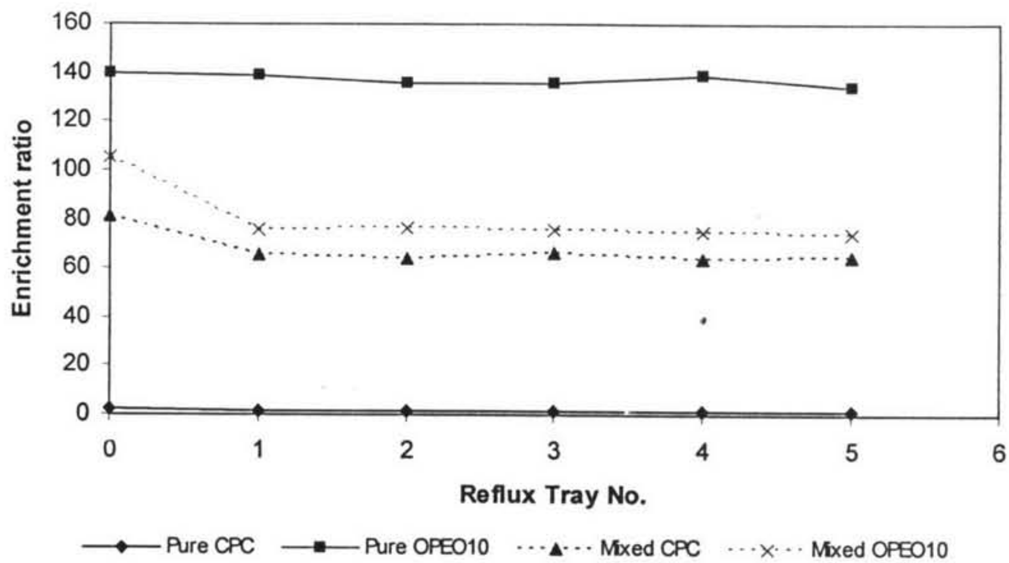

Figure 4.31 Effect of Reflux Position on the enrichment ratio of each surfactant of the mixed-surfactant system under operational condition of [total surfactant] = 0.225 mM; molar ratio of CPC to $OPEO_{10}$ = 1:1; feed position = tray number 5.

4.6.3 Effect of Reflux Ratio

In this part of study, the effect of the reflux ratio in the foam fractionation column of the mixed-surfactant system on the separation performance is shown in Figures 4.32 and 4.33. As seen from these figures, both the %surfactant recovery and the enrichment ratio of $OPEO_{10}$ in the mixed-surfactant system were not as significant when the reflux ratio was increased. In contrast, the %surfactant recovery of CPC was decreased when increasing the reflux ratio. Interestingly, under the studied conditions, both the enrichment ratio and the %surfactant recovery of $OPEO_{10}$ were much higher than those of CPC for the same reason discussed in the previous section. The values of the enrichment ratio are intermediate between those of pure CPC and $OPEO_{10}$ system but the %surfactant recovery shows the opposite result. The reflux ratio had strongly effect on %CPC recovery as shown in Figure 4.32.

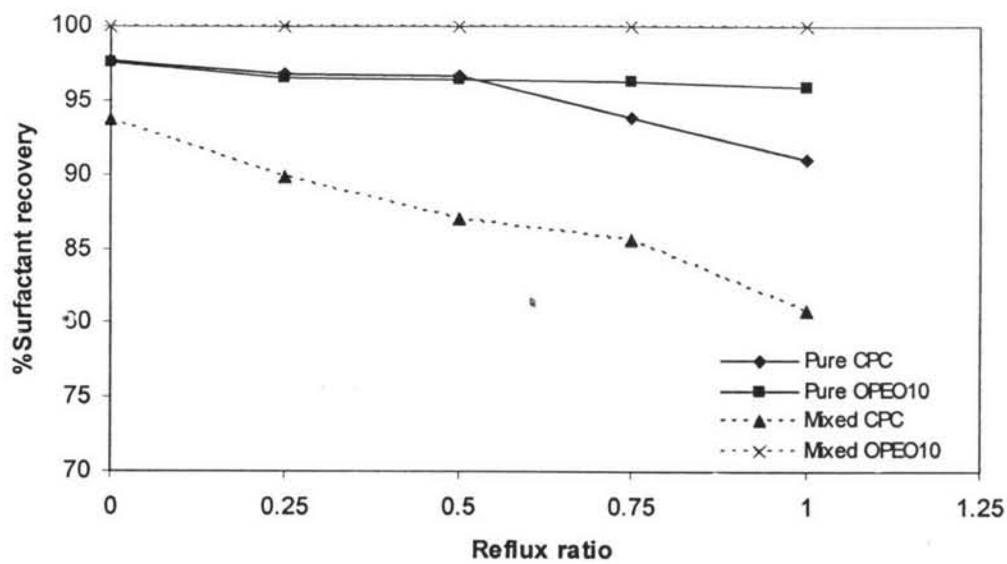

Figure 4.32 Effect of Reflux Ratio on the %surfactant recovery of each surfactant of the mixed-surfactant system under operational condition of [total surfactant] = 0.225 mM; molar ratio of CPC to $OPEO_{10}$ = 1:1; feed position = tray number 5; reflux position = tray number 1.

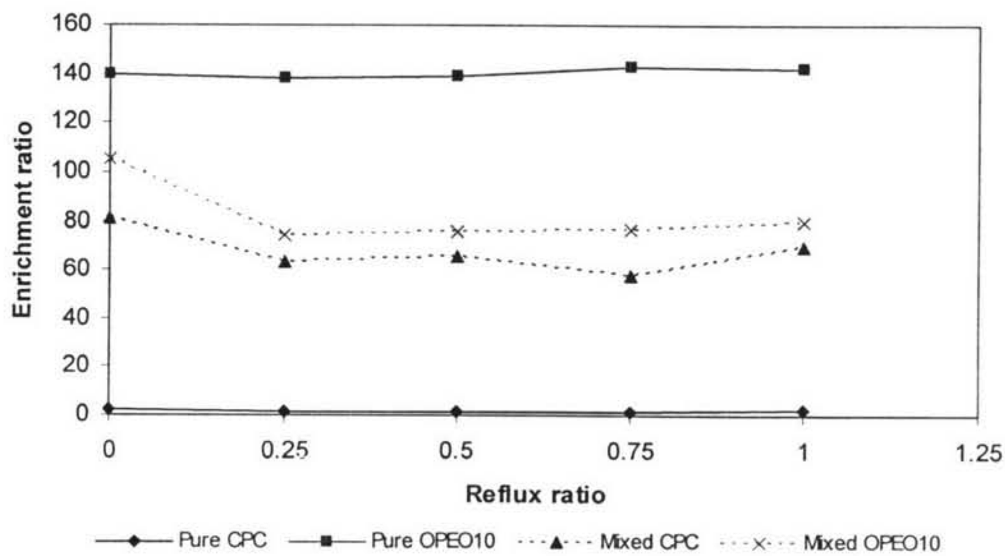

Figure 4.33 Effect of Reflux Ratio on the enrichment ratio of each surfactant of the mixed-surfactant system under operational condition of [total surfactant] = 0.225 mM; molar ratio of CPC to $OPEO_{10}$ = 1:1; feed position = tray number 5; reflux position = tray number 1.