# 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.

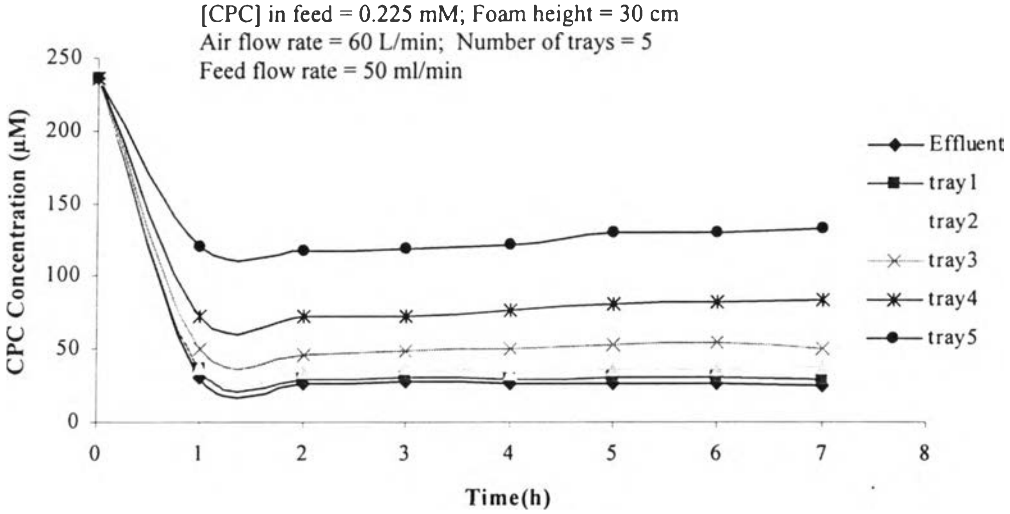

**Figure 4.1** Concentration profiles with respect to time.

## 4.2 Operating Limits

The operating limits of the multistage foam fractionator were determined by varying both air and feed flowrates. Two important operational constraints; foam formation and flooding, are considered as the limits of the operation of foam fractionation. A sufficient air flow rate is needed to produce foam which can reach the foam outlet at the top stage. On the other hand, flooding depends on both liquid flow rate and the air flow rate. For any given liquid flow rate, the flooding condition occurrs at very high air flow rates for which flow reversal occurs and the liquid is carried upward. Figure 4.2 shows the boundary of the operational region of the foam fractionator used in this study. 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.

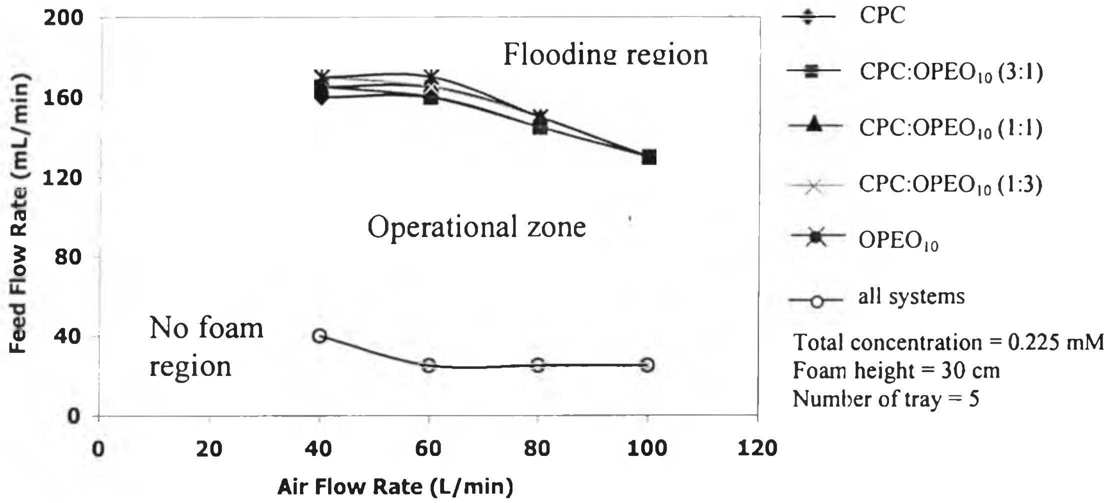

**Figure 4.2** Operational zone of the five-stage foam fractionation column.

### 4.3 Critical Micelle Concentrations (CMC) of Single and Mixed Surfactants

An increase in the $OPEO_{10}$ to CPC ratio causes a reduction of the CMC. From Figure 4.3, it can be seen that the CMC of the mixed-surfactant (CPC and $OPEO_{10}$) system is much lower than that of the pure CPC system. The CMC of $OPEO_{10}$ of 300 μM is considerably much lower than that of CPC (900 μM). $OPEO_{10}$ is a nonionic surfactant which can form micelles much easier than CPC, cationic surfactant since the repulsive force between the $OPEO_{10}$ head groups is much lower than that of CPC. An increase in $OPEO_{10}$ to CPC ratio will reduce the repulsive force between group of CPC resulting in forming micelles easierly and lowering the CMC. Table 4.1 shows the measured values of the CMC at different ratios of CPC to $OPEO_{10}$ as compared to those of pure CPC and pure $OPEO_{10}$.

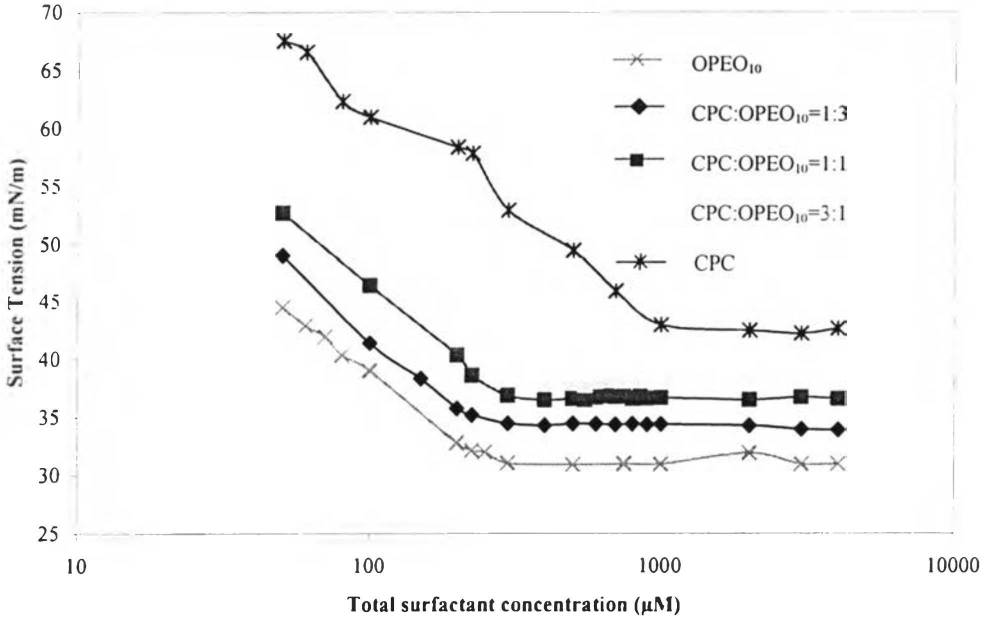

**Figure 4.3** Surface tension as a function of total surfactant concentration of single and mixed surfactant systems at different molar ratios.

**Table 4.1** The measured values of the CMCs of pure and mixed surfactants at different CPC to $OPEO_{10}$ ratios

| Type of surfactants | CMC (µM) |
|---|---|
| CPC | 900 |
| Mixed CPC:$OPEO_{10}$ | 300-400 |
| $OPEO_{10}$ | 300 |

## 4.4 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 both CPC and $OPEO_{10}$. Efficiency of the surfactant separation was evaluated in terms of %surfactant recovery and enrichment ratio as defined below:

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

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

where $C_i$ and $C_e$ are the surfactant concentrations (mM) in the influent and effluent streams, respectively

$C_f$ is the surfactant concentration in the collapsed foam stream

It is important to note that once the surfactant concentration in all streams were measured, mass balance around the studied fractionator was performed to determine reliability of the experimental data. It was found that the mass balance for any surfactant was close within at least 90% for all runs. The deviation mainly came from fluctuations in the foam flow rates and low surfactant concentrations in the effluent liquid streams.

### 4.4.1 Effect of Air Flow Rate

Figures 4.4 and 4.5 show the effects of the air flow rate on the separation efficiencies of two pure surfactants of CPC and $OPEO_{10}$. As mentioned before, the lowest air flow rate of 40mL/min was needed to operate the studied foam fractionator. Thus, the air flow rate lower than this resulted in such a low production of foam that did collapse before reaching the overflow pipe. As can be seen from Figures 4.4 and 4.5, an increase in air flow rate results in a reduction in the enrichment ratio but the %surfactant recovery increases for either CPC or $OPEO_{10}$. An increase in the air flow rate tends to produce a wetter foam because of more bubbles generated to lower the liquid drainage rate, resulting in lowering the enrichment ratio. As the air flow rate increases, a higher volumetric rate of foam is generated resulting in increasing the surfactant recovery. Figure 4.6 shows the comparison of surfactant separation performance between pure CPC and pure $OPEO_{10}$ systems. In comparison, the $OPEO_{10}$ recovery, in the range of 90-97% was higher than the CPC recovery in the range of 80-95%. This is because the foam ability of $OPEO_{10}$ is much higher than that of CPC while the foam stability is not much different as shown in Table 4.2. The higher foam ability and the lower foam stability of the $OPEO_{10}$ system results in having much higher enrichment ratio as compared to the CPC system. Interestingly, when compared the separation efficiencies of CPC obtained from the present study to those of the previous work it was found that the values of both enrichment ratio and %surfactant recovery of CPC in the present study are much higher than those of the previous work as seen in 4.6. This is because the present foam fractionation has more contains more bubble caps (22 per tray) than the previous unit (8 per tray). An increase in the number of bubble caps increases the interfacial area between gas and liquid phases leading to an increase in the mass transfer of surfactant.

**Table 4.2** Foam stability and foam ability of pure CPC and pure $OPEO_{10}$ systems at initial surfactant concentration of 0.225 mM

| Type of Surfactants | Foam stability (min) | Foam ability |
|---|---|---|
| CPC | 6.46 | 2.1 |
| $OPEO_{10}$ | 5.51 | 3.8 |

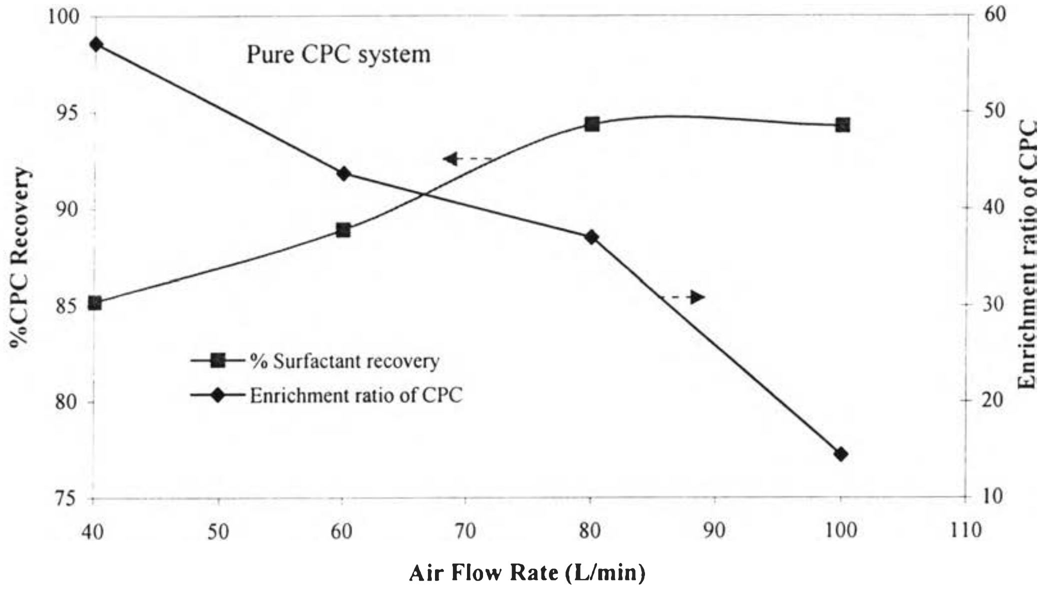

**Figure 4.4** Effects of superficial air velocity under operational conditions of [CPC] = 0.225 mM; feed flow rate = 50 ml/min and foam height = 30 cm.

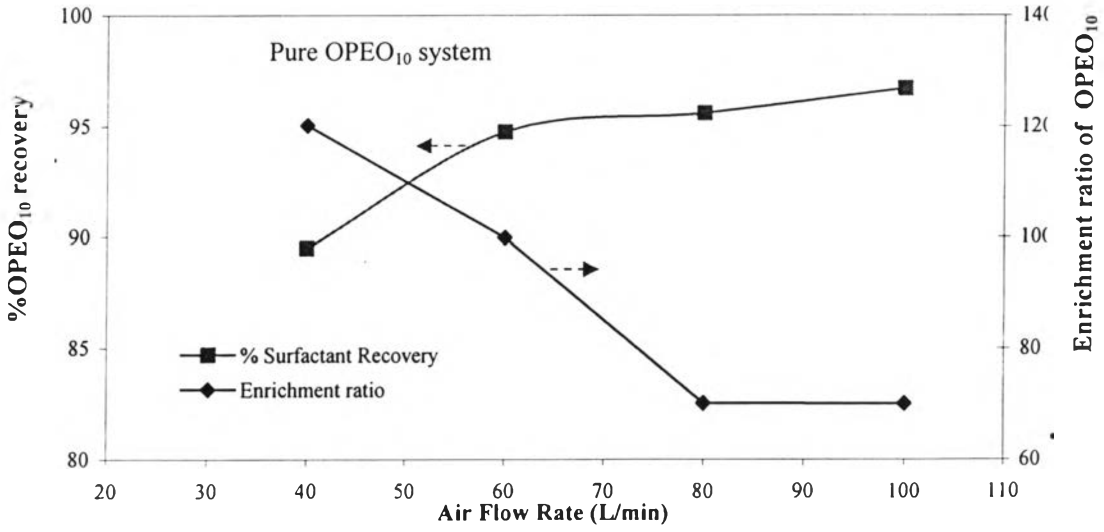

**Figure 4.5** Effects of superficial air velocity under operational conditions of [OPEO$_{10}$] = 0.225 mM; feed flow rate = 50 ml/min and foam height = 30 cm.

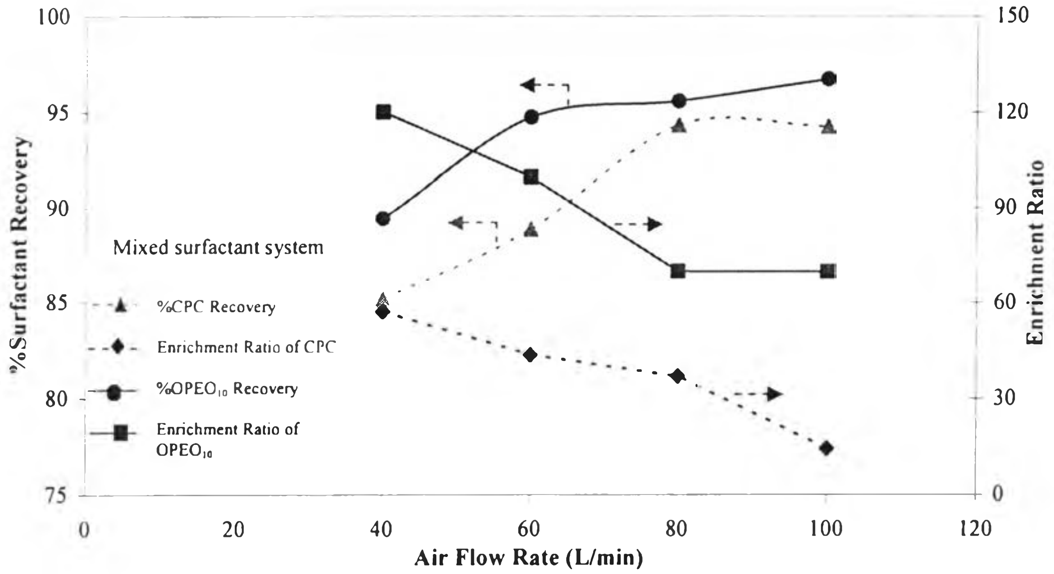

**Figure 4.6** Comparison of surfactant recovery between pure CPC and $OPEO_{10}$ system operated at [surfactant] = 0.225 mM; feed flow rate = 50 ml/min and foam height = 30 cm.

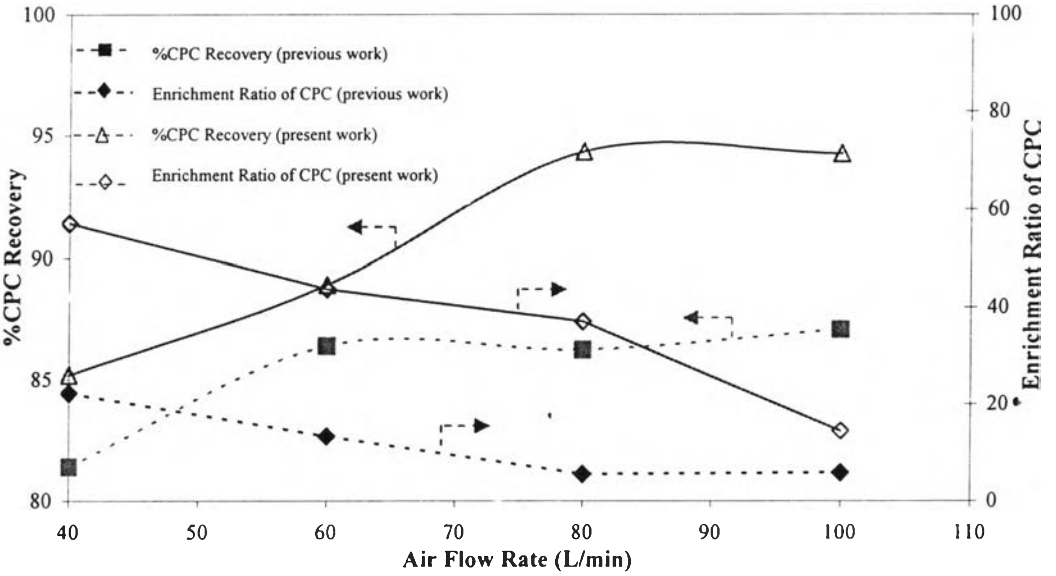

**Figure 4.7** Effects of superficial air velocity on separation efficiencies of CPC as compared to the previous results under operational conditions [CPC] = 0.225 mM; feed flow rate = 50 ml/min and foam height = 30 cm.

### 4.4.2 Effect of Liquid Feed Flow Rate

The effects of the liquid feed flow rate on the separation efficiencies of CPC and $OPEO_{10}$ are shown in Figures 4.8 and 4.9, respectively. An increase in the feed flow rate results in a decrease in both enrichment ratio and %surfactant recovery because the residence time is shortened at a higher liquid flow rate, thus a higher amount of surfactant still remains in the liquid phase. For all conditions studied. the enrichment ratio and the surfactant recovery of $OPEO_{10}$ as high as 380 and 97%, respectively, were achieved at the lowest liquid feed flow rate of 25 mL/min. From Figure 4.10, it can be seen that the effectiveness of foam fractionation process in recovering nonionic surfactant ($OPEO_{10}$) is better than for cationic surfactant (CPC) which can be explained by foam stability and foam ability for the same reason discussed in the previous section. Figure 4.11 shows a comparison between the separation efficiencies of CPC from this work to those of previous work, the results showed that the values of both enrichment ratio and %surfactant recovery which were obtained from previous study are lower than those of this work. The mass transfer surface area is higher as number of bubble caps per tray increases, which in turn leads to higher enrichment ratio and %surfactant recovery for the same reason discussed in the previous section.

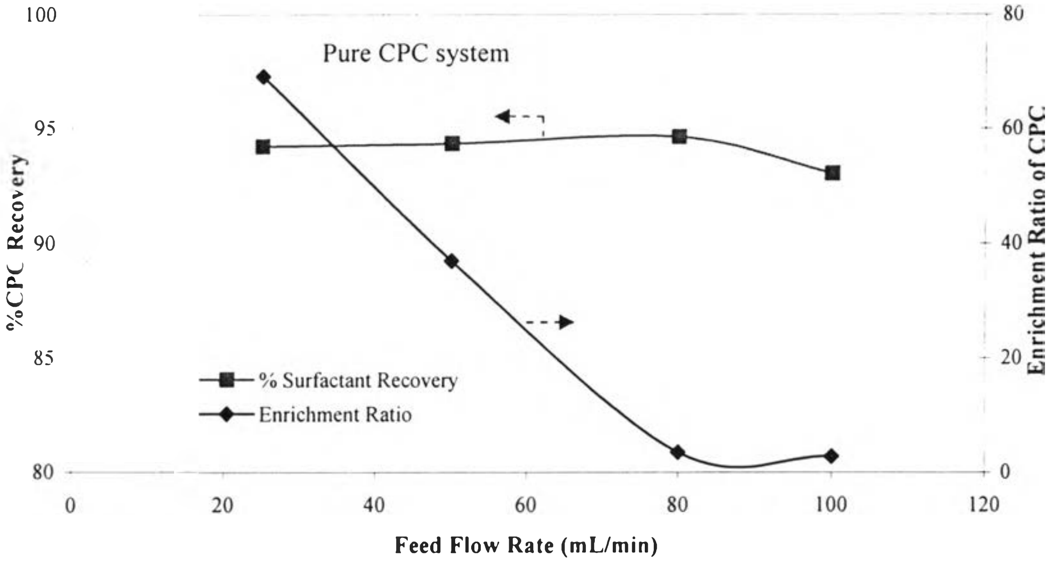

**Figure 4.8** Effects of liquid feed flow rate under operational conditions of [CPC] = 0.225 mM; air flow rate = 80 L/min and foam height = 30 cm.

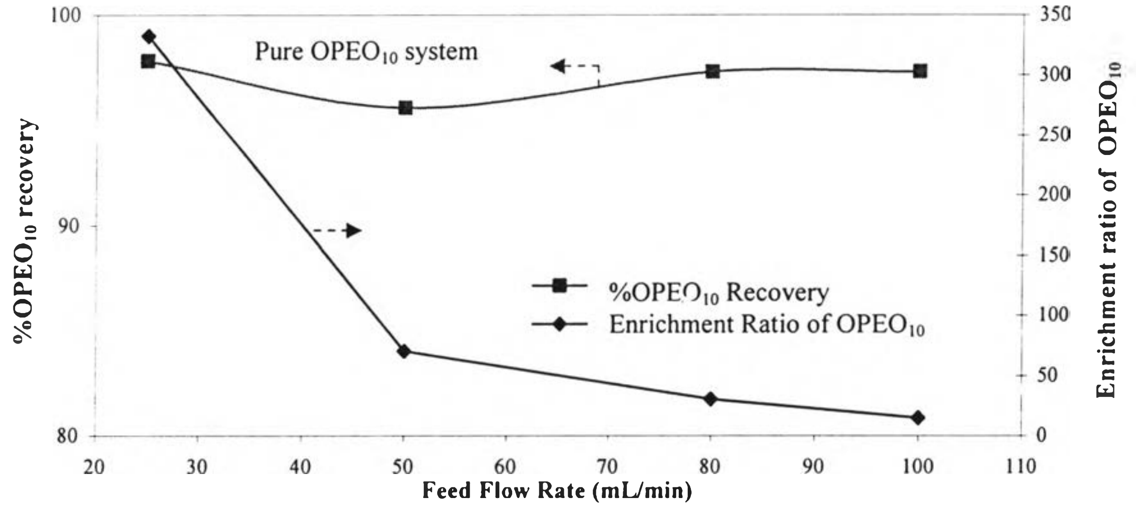

**Figure 4.9** Effects of liquid feed flow rate under operational conditions of [OPEO$_{10}$] = 0.225 mM; air flow rate = 80 L/min and foam height = 30 cm.

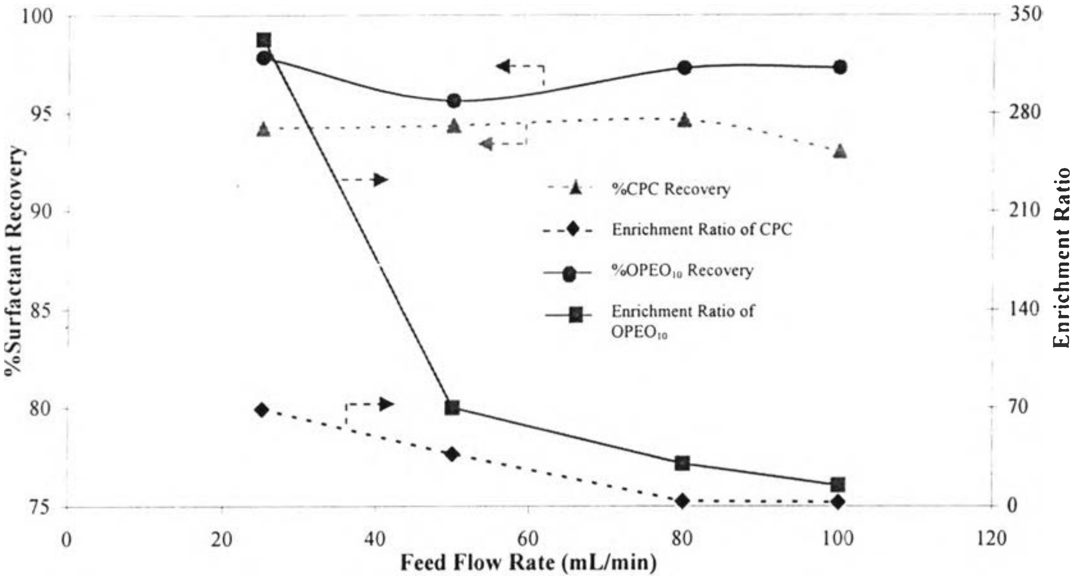

**Figure 4.10** Comparison of surfactant separation performance between pure CPC and OPEO$_{10}$ operated at [surfactant] = 0.225 mM; air flow rate = 80 ml/min and foam height = 30 cm.

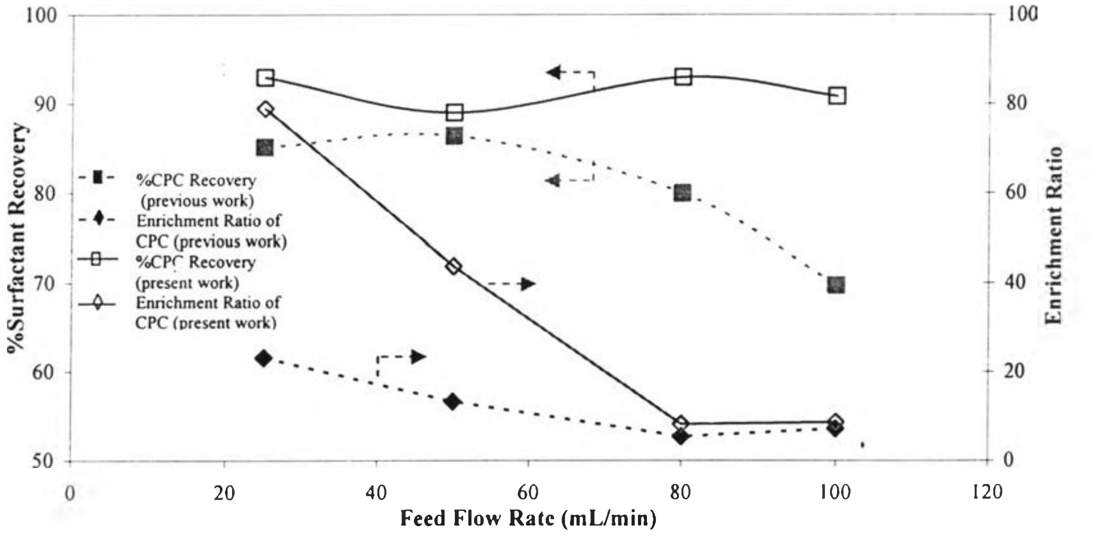

**Figure 4.11** Comparison of surfactant separation performance between the present work and the previous work operated at [CPC] = 0.225 mM; air flow rate = 60 L/min and foam height = 30 cm.

### 4.4.3 Effect of Foam Height

The effect of foam height (distance between the top of liquid surface on the highest tray and the overflow pipe) was studied by varying from 30 to 90 cm. Figures 4.12 and 4.13 illustrate the influence of foam height on the surfactant separation efficiencies of pure CPC and $OPEO_{10}$ systems, respectively. For this study, a liquid feed flow rate of 25 mL/min was found that the feed flow rate was too low to produce foam to reach a foam height of 90 cm. Hence, the system was operated at a higher feed flow rate of 50 mL/min. An increase in foam height resulted in increasing enrichment ratio but it led to a subtle decrease in %surfactant recovery for both CPC and $OPEO_{10}$ systems as seen in Figures 4.12 and 4.13, respectively. For all conditions, the surfactant recovery of CPC and $OPEO_{10}$ were in the range of 85-95% and 90-95%, respectively. An increase in foam height leads to a longer foam residence time, which allows more drainage of the water in the films resulted in a dryer foam. The surfactant recovery decreased slightly with increasing foam height because of the increased rate of foam collapse due to foam drainage. The results agree well with the previous work (Tharapiwattananon, 1995). A comparison of the surfactant separation efficiencies between CPC and $OPEO_{10}$ systems is shown in Figure 4.14, the results indicate that the values of both enrichment and %surfactant recovery of pure $OPEO_{10}$ system is higher than those of pure CPC system. As expected, $OPEO_{10}$, nonionic surfactant can produce foam much better than CPC, cationic surfactant.

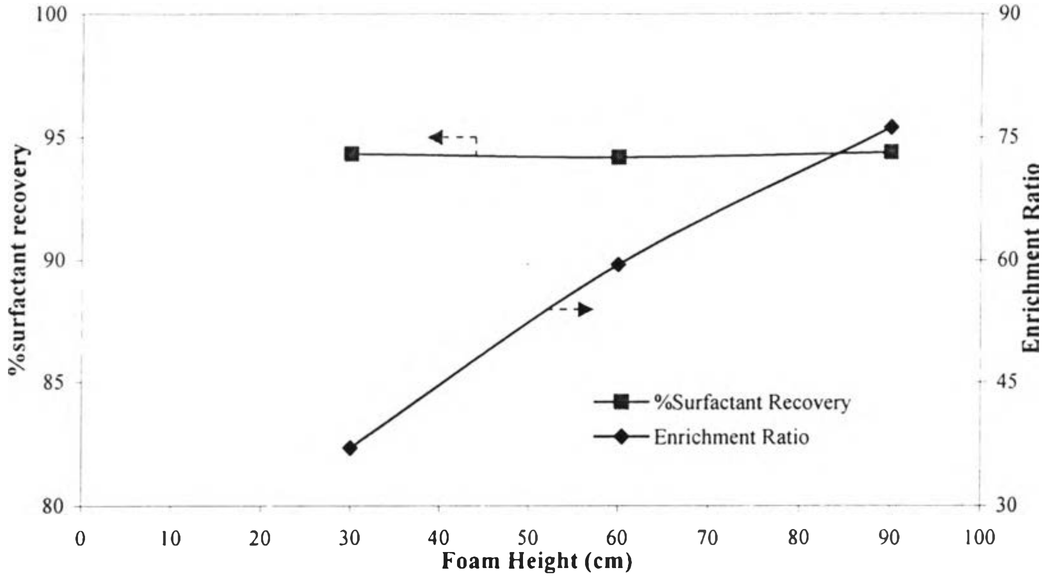

**Figure 4.12** Effect of foam height on separation efficiencies of CPC system operated at [CPC] = 0.225 mM; air flow rate = 80 L/min and feed flow rate = 50 ml/min.

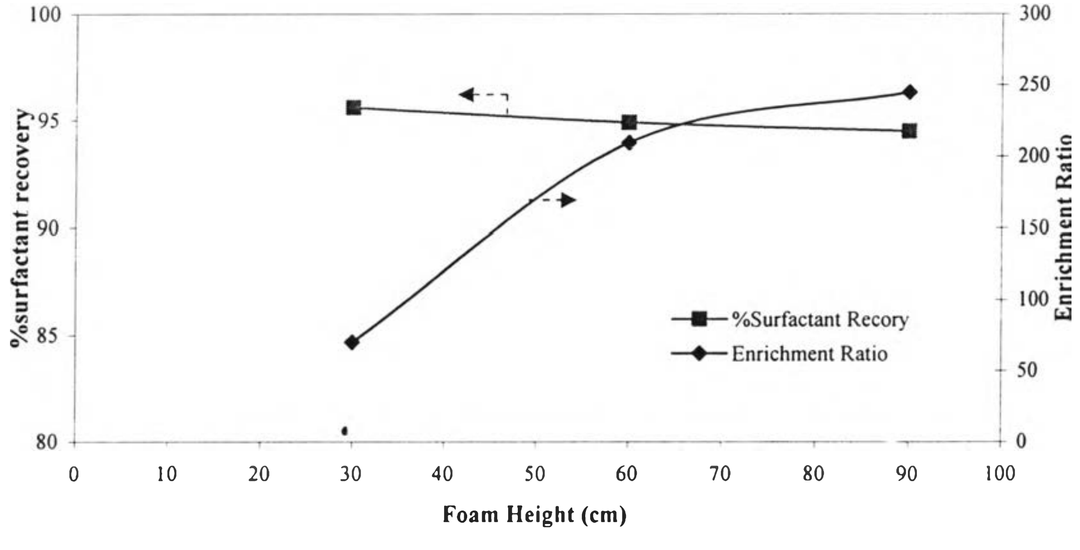

**Figure 4.13** Effect of foam height on separation efficiencies of $OPEO_{10}$ system operated at $[OPEO_{10}]$ = 0.225 mM, air flow rate = 80 L/min and feed flow rate = 50 ml/min.

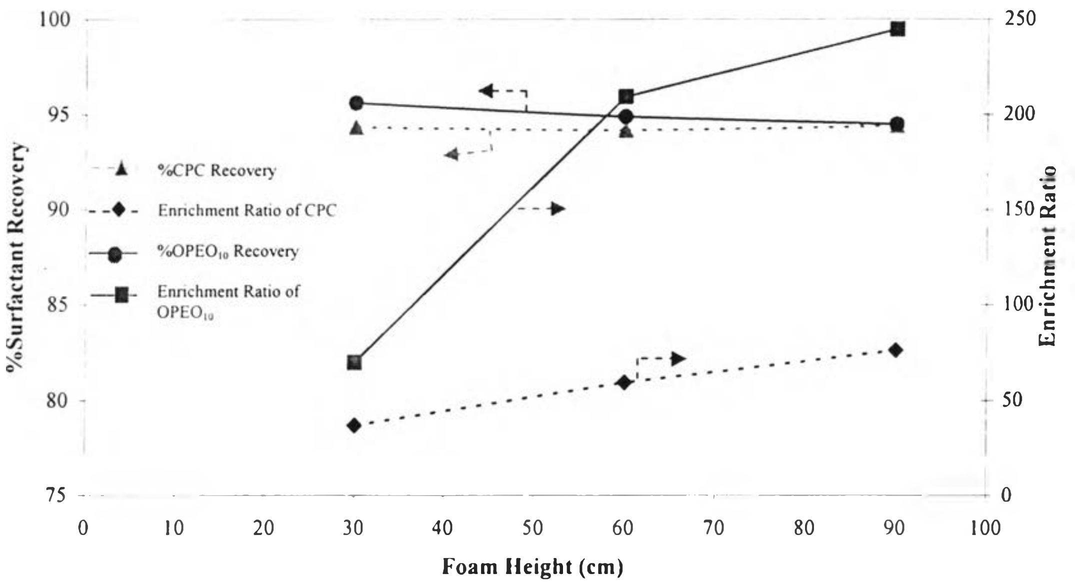

**Figure 4.14** Comparison of the effect of foam height on separation efficiency between CPC and $OPEO_{10}$ systems operated at [surfctant] = 0.225 mM, air flowrate = 80 L/min and feed flow rate = 50 mL/min.

### 4.5 Foam characteristics of Single and Mixed Surfactant Systems

foam characteristics in terms of stability and foam ability of single-surfactant and mixed-surfactant systems at constant total concentration of 0.225 mM are shown in Figures 4.15 and 4.16, respectively. In comparison between pure CPC and $OPEO_{10}$ system, the foam stability of pure CPC system is higher than that of pure $OPEO_{10}$ as shown in Figure 4.15. It can be explained that the repulsive force between the layer 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 $OPEO_{10}$. As can be seen from Figure 4.15, 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. When considered all the mixed surfactant systems, the foam stability of the mixed surfactant system having a molar ratio of CPC to $OPEO_{10}$ of 3:1 was higher than those of ratio 1:1 and 1:3. The possibility of explanation is that with a small amount of $OPEO_{10}$ added (for the case of 3:1 molar ratio of CPC to $OPEO_{10}$), it can reduce the repulsive force between the positive head groups of CPC. As a result, there are more CPC molecules adsorbing on the air/liquid interface of foam leading to increasing the repulsive interaction between two layers of the lamellae. If a high amount of $OPEO_{10}$ added (for the case of 1:1 and 1:3 molar ratios of CPC to $OPEO_{10}$), $OPEO_{10}$ adsorption becomes more competitive resulting in lowering CPC adsorption onto the air/liquid interface of foam. Consequently, the repulsive interaction of the two parallel film of lamellae decreases. Figure 4.16 depicts the observed foam ability of CPC, $OPEO_{10}$ and the mixed surfactant systems. As shown in Figure 4.16, the pure CPC system has the lowest foam ability and foam ability increases with increasing $OPEO_{10}$ ratio. Possible explanation is that the lower surface tension leads to the easier to form foam, thus resulting in the higher foam ability. As can be seen from Figure 4.3, for any given total surfactant concentration lower than the CMC, the CPC system has the highest surface tension and the surface tension decreases with increasing $OPEO_{10}$ ratio.

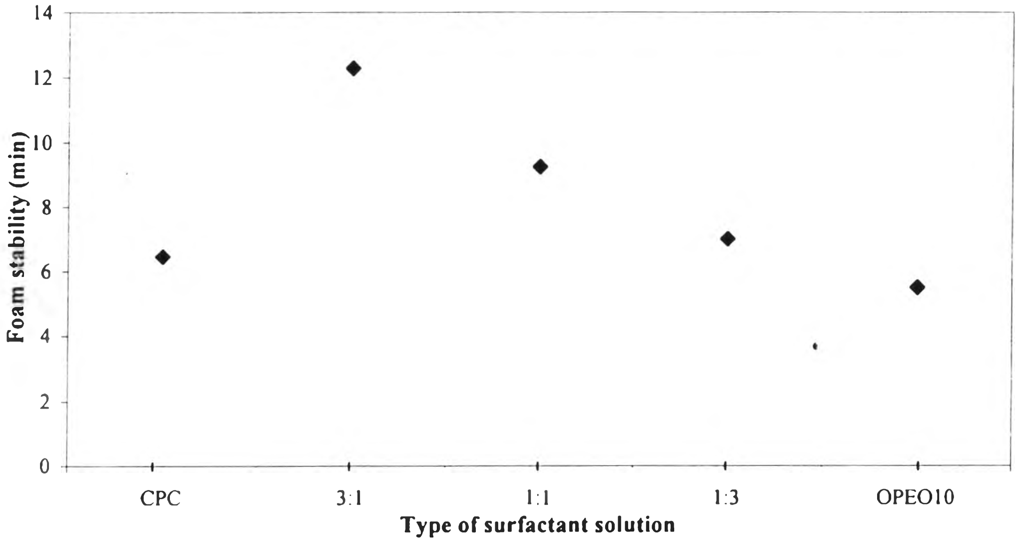

**Figure 4.15** Foam stability of various types of surfactant solutions operated at total surfactant concentration = 0.225 mM; air flow rate = 0.1 L/min and surfactant solution = 250 ml.

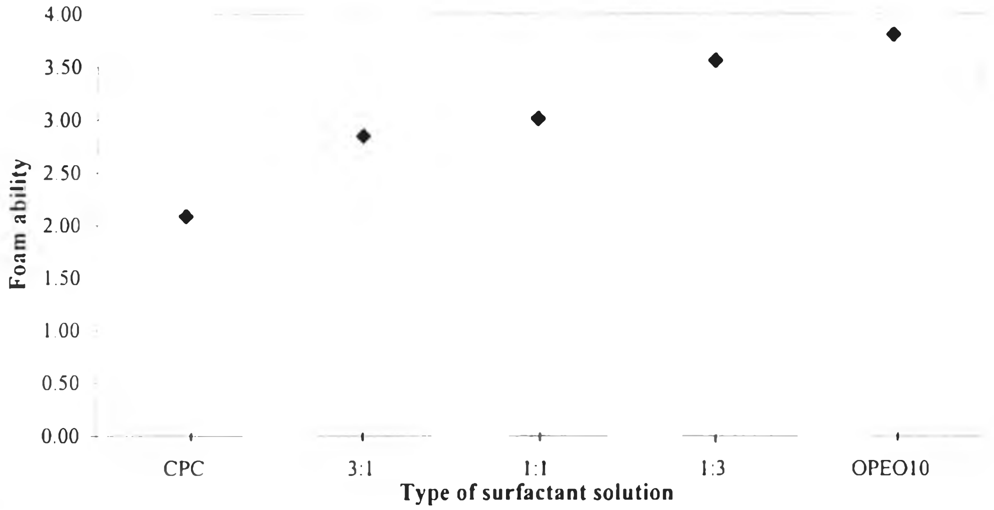

**Figure 4.16** Foam ability of various surfactant systems operated at total surfactant concentration = 0.225 mM; air flow rate = 0.1 L/min and surfactant solution = 250 ml.

## 4.6 Multi-stage Foam Fractionator Efficiencies of Mixed Surfactant Systems

In this part of the study, the effects of various parameters such as air flow rate, liquid feed flow rate, and foam height 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 and 5 trays. In the mixed CPC/OPEO10 systems, the separation efficiencies are presented in terms of %surfactant recoveries and enrichment ratios of total surfactants and each surfactant as given below:

$$\text{Surfactant Recovery (\%)} = \frac{C_{i,n} - C_{e,n} \times 100}{C_i}$$

$$\text{Enrichment Ratio} = C_{f,n} / C_{i,n}$$

where $C_i$ and $C_e$ are the surfactant concentrations (mM) in the influent and effluent streams, respectively.

$C_f$ is the surfactant concentration in the collapsed foam stream.

and subscript n refers to either CPC, $OPEO_{10}$ and total.

### 4.6.1 Effect of Air Flow Rate

The effect of the air flow rate on the separation efficiencies of mixed surfactant systems at different molar ratios of CPC to $OPEO_{10}$ (3:1, 1:1, and 1:3 ) is shown in Figures 4.17-4.22. From these figures, the same trend was observed that increasing air flow rate resulted in a decrease in enrichment ratio and an increase in %surfactant recovery. Figures 4.17, 4.19 and 4.21 show the effect of air flow rate on the separation efficiencies of each surfactant at different molar ratios of CPC to $OPEO_{10}$. For any mixed surfactant system with any given air flow rate, the values of enrichment ratio and %surfactant recovery 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. This is because the foam stability of all mixed surfactant systems is higher than that of the pure OPEO10 system as shown in Figure 4.15. The surfactant recovery of $OPEO_{10}$ is almost 100% as seen in Figures 4.17, 4.19, and 4.21, presumably due to the higher foam stability resulting in a lower drainage rate, thus a decrease rate of foam collapse. As a result, %surfactant recovery increases. Figures 4.18, 4.20, and 4.22 show the separation efficiencies of total surfactants at CPC to $OPEO_{10}$ molar ratios of 3:1, 1:1, 1:3, respectively. The values of both total surfactant enrichment ratio and %total surfactant recovery of these three mixed surfactant systems are intermediate between those of pure CPC and $OPEO_{10}$ systems.

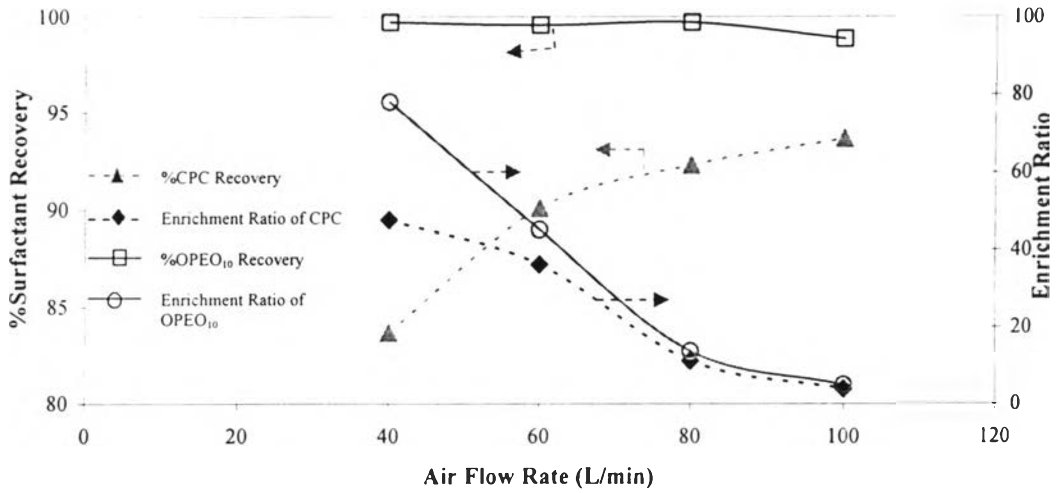

**Figure 4.17** Effect of superficial air velocity on separation efficiencies of each surfactant of 3:1 mixed surfactant system operated at operated at molar ratio of CPC to $OPEO_{10}$ = 3:1, [total surfactants] = 0.225 mM, feed flow rate = 50 mL/min and foam height = 30 cm.

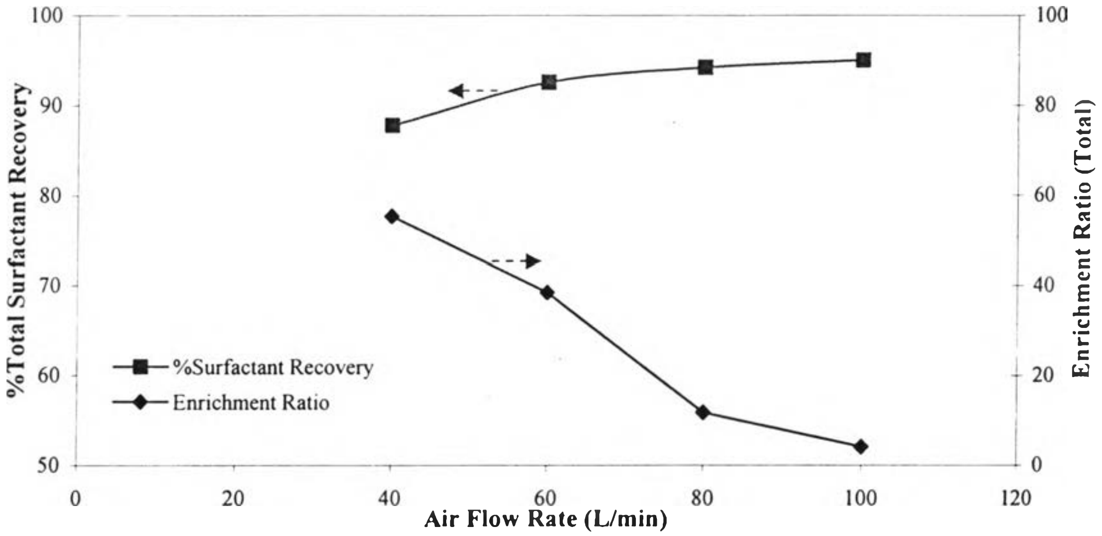

**Figure 4.18** Effect of superficial air velocity on separation efficiencies of 3:1 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 3:1, [total surfactants] = 0.225 mM, feed flow rate = 50 mL/min and foam height = 30 cm.

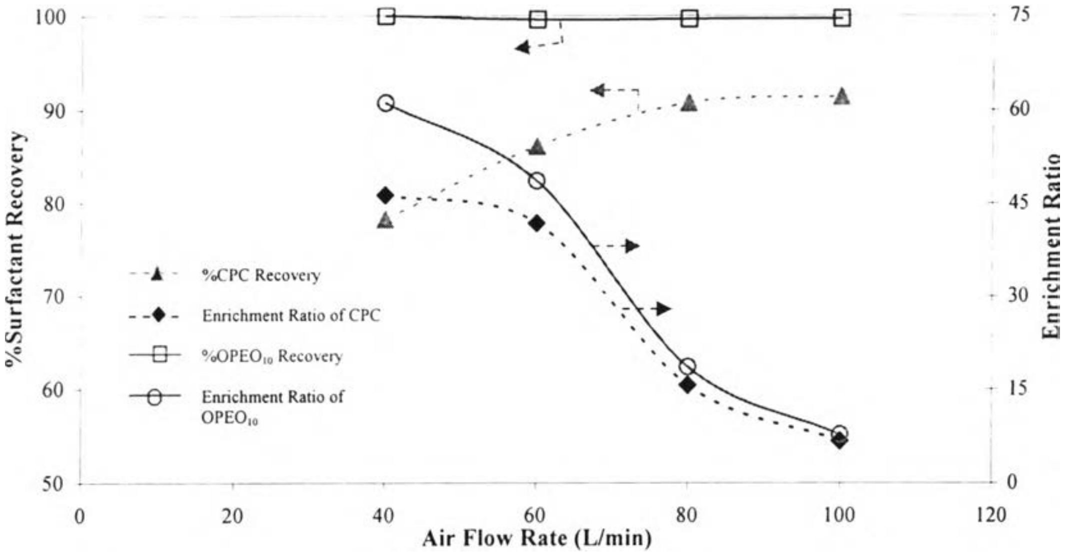

**Figure 4.19** Effect of superficial air velocity on separation efficiencies of CPC or $OPEO_{10}$ of 1:1 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:1, [total surfactants] = 0.225 mM, feed flow rate = 50 mL/min and foam height = 30 cm.

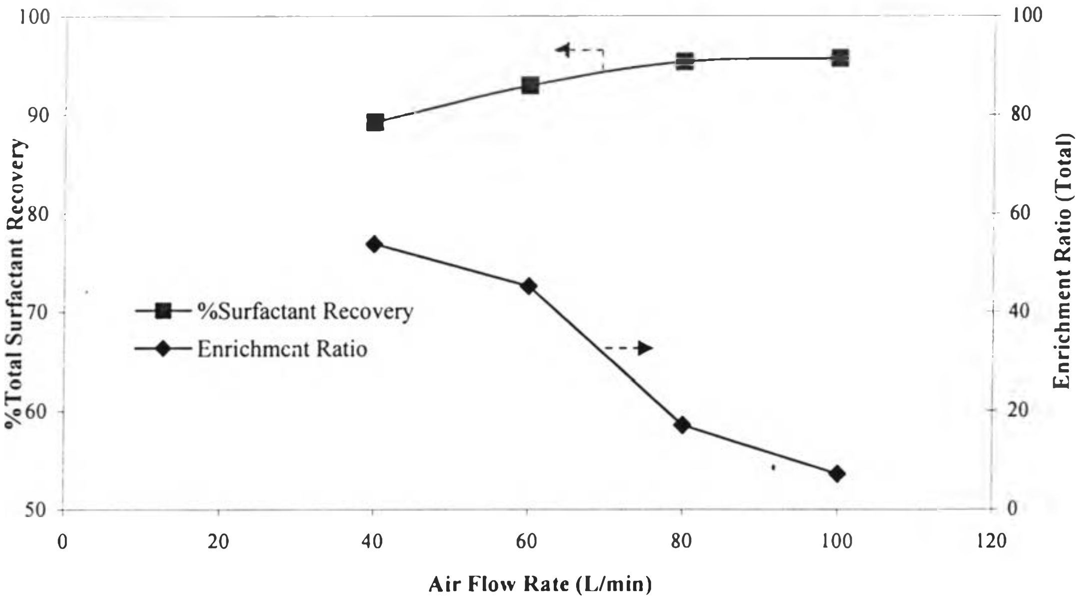

**Figure 4.20** Effect of superficial air velocity on total surfactant separation efficiencies of 1:1 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:1, [total surfactants] = 0.225 mM, feed flow rate = 50 mL/min and foam height = 30 cm.

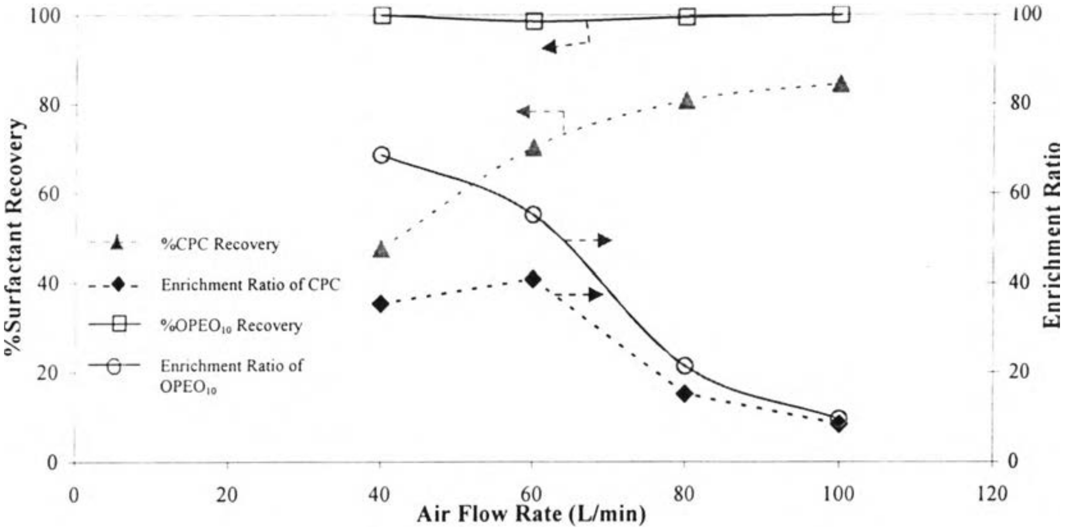

**Figure 4.21** Effect of superficial air velocity on separation efficiencies of each surfactant of 1:3 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:3, [total surfactants] = 0.225 mM, feed flow rate = 50 mL/min and foam height = 30 cm.

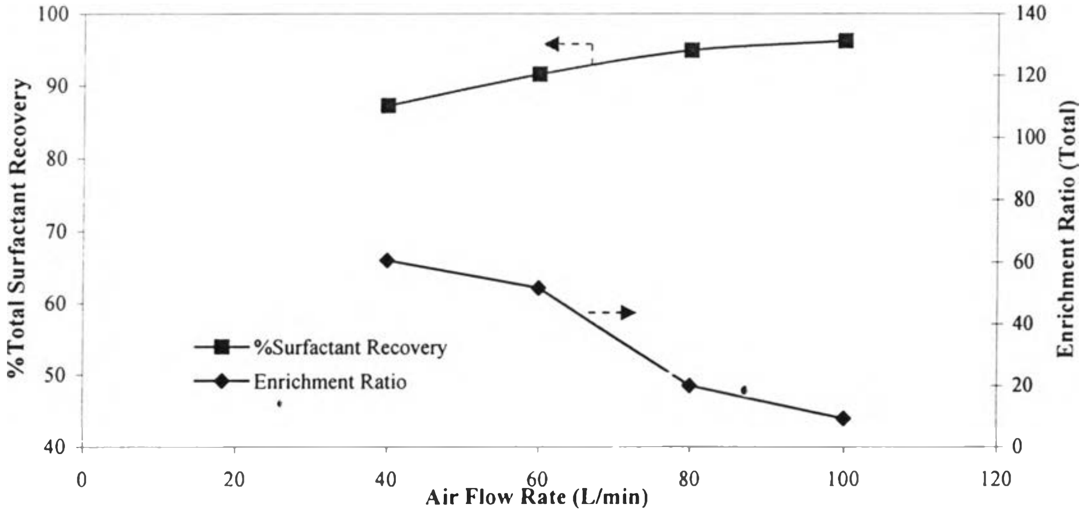

**Figure 4.22** Effect of superficial air velocity on total surfactant separation efficiencies of 1:3 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:3, [total surfactants] = 0.225 mM, feed flow rate = 50 mL/min and foam height = 30 cm.

### 4.6.2 Effect of Liquid Feed Flow Rate

The effects of liquid feed flow rate are shown in Figures 4.23-4.28. Figures 4.23, 4.25, and 4.27 depict the effect of liquid feed flow rate on the separation efficiencies of each surfactant of mixed surfactant systems having different molar ratios of CPC to $OPEO_{10}$. When comparing the separation efficiencies of CPC and $OPEO_{10}$, it can be seen that for any given feed flow rate, both the enrichment ratio and %surfactant recovery of $OPEO_{10}$ were higher than those of CPC. According to these figures, both enrichment ratio and %surfactant recovery of CPC in mixed system decreased as the liquid feed flow rate increased. The possible explanation is the same discussed in the single surfactant systems. In contrast, a slight decrease in the $OPEO_{10}$ recovery with increasing liquid feed flow rate since the systems were operated under a relatively low range of the feed flow rate. Figures 4.24, 4.26, and 4.28 show the separation efficiencies of total surfactants at the mixed surfactant systems having different molar ratios of CPC to $OPEO_{10}$ 3:1, 1:1, 1:3, respectively. An increase in the flow rate of liquid feed resulted in decreasing in both enrichment ratio and %surfactant recovery of the total surfactants. However, the values of both enrichment ratio and %surfactant recovery are intermediate between those of pure CPC and $OPEO_{10}$ system.

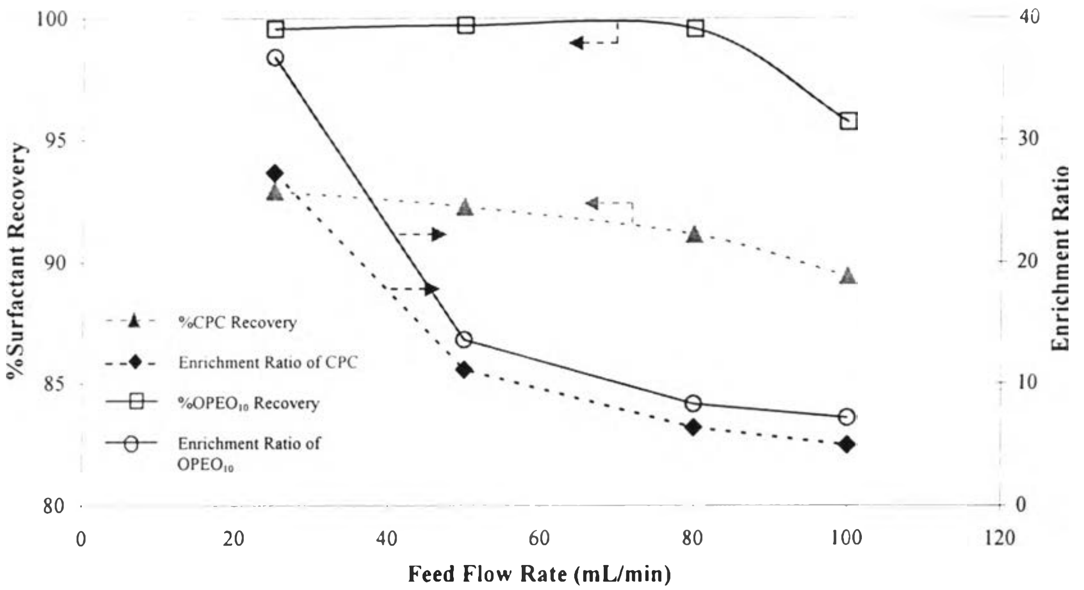

**Figure 4.23** Effect of liquid feed flow rate on separation efficiencies of each surfactant of 3:1 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 3:1, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and foam height = 30 cm.

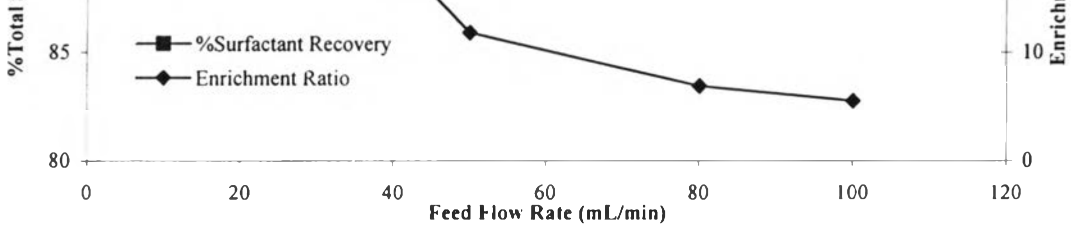

**Figure 4.24** Effect of liquid feed flow rate on total surfactant separation efficiencies of mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 3:1, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and foam height = 30 cm.

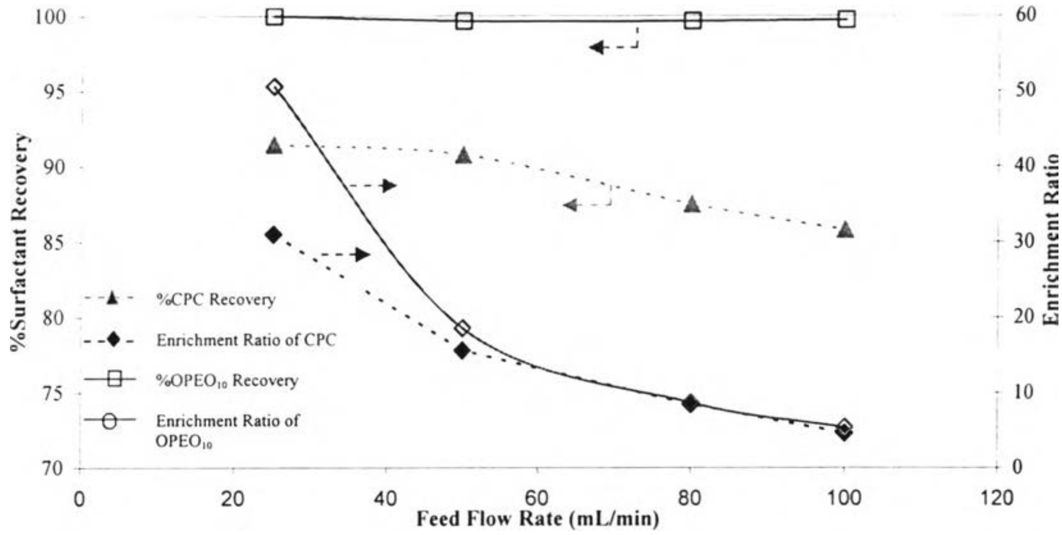

**Figure 4.25** Effect of liquid feed flow rate on separation efficiencies of each surfactant of 1:1 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:1, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and foam height = 30 cm.

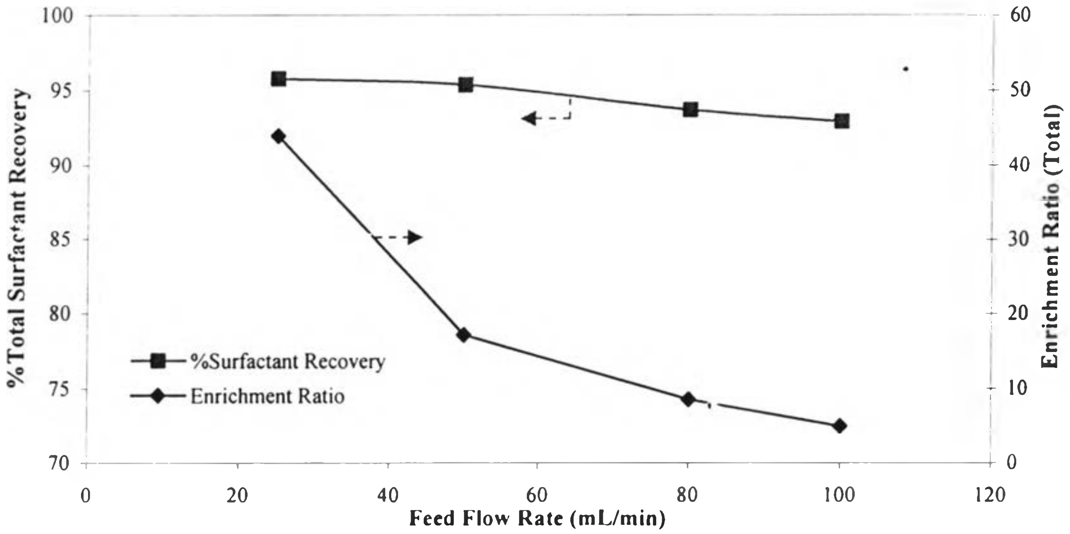

**Figure 4.26** Effect of liquid feed flow rate on total surfactant separation efficiencies of mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:1, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and foam height = 30 cm.

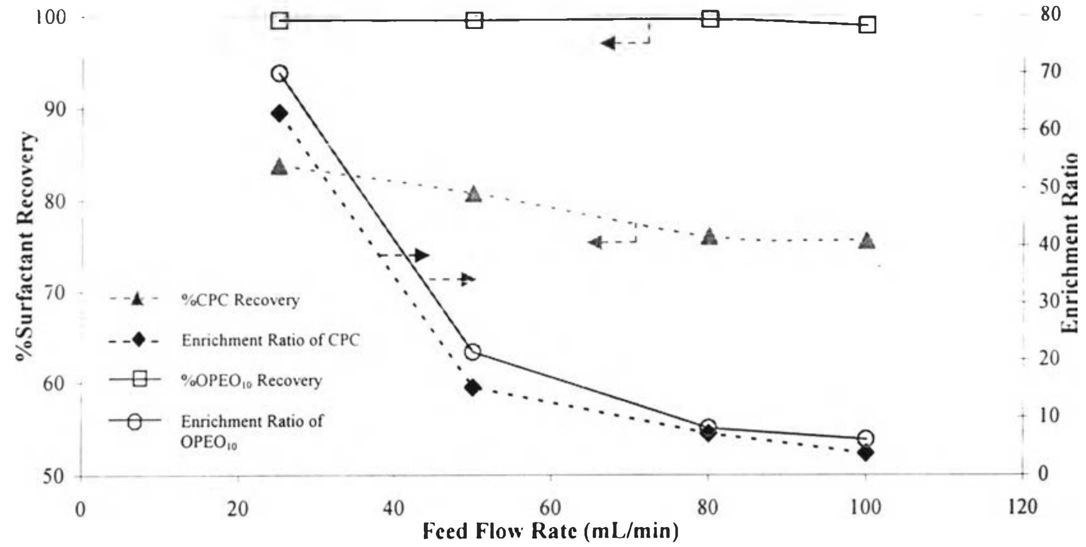

**Figure 4.27** Effect of liquid feed flow rate on separation efficiencies of each surfactant of 1:3 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:3, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and foam height = 30 cm.

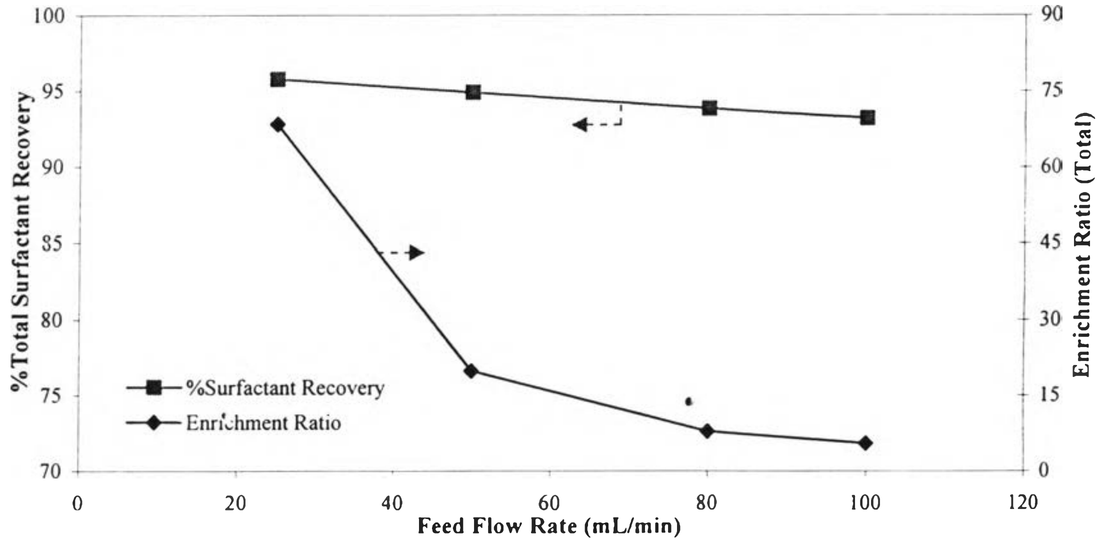

**Figure 4.28** Effect of liquid feed flow rate on total surfactant separation efficiencies of mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:3, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and foam height = 30 cm.

### 4.6.3 Effect of Foam Height

In this part of study, the effects of the foam height in the foam fractionation column of the mixed-surfactant systems having different molar ratios of CPC to $OPEO_{10}$ on separation performance are shown in Figures 4.29-4.34. As seen from these figures, for either each or total surfactants the effect of foam height on the surfactant recovery was not as significant as it was on the enrichment ratio. An increase in foam height resulted in increasing the enrichment ratio and led to a subtle decrease in %surfactant recovery which can be explained for the same reason discussed in the single surfactant system. Interestingly, under the studied conditions, both enrichment ratio and %surfactant recovery of $OPEO_{10}$ were much higher than those of CPC. This can probably be attributed to the presence of CPC in the mixed surfactant systems leading to a higher foam stability and foam ability as shown in Figures 4.15 and 4.16. As mentioned before, the CMC of $OPEO_{10}$ is lower than that of CPC indicating that $OPEO_{10}$ can adsorb in the foam phase more than CPC. As a result, the recovery of $OPEO_{10}$ is greater than that of CPC.

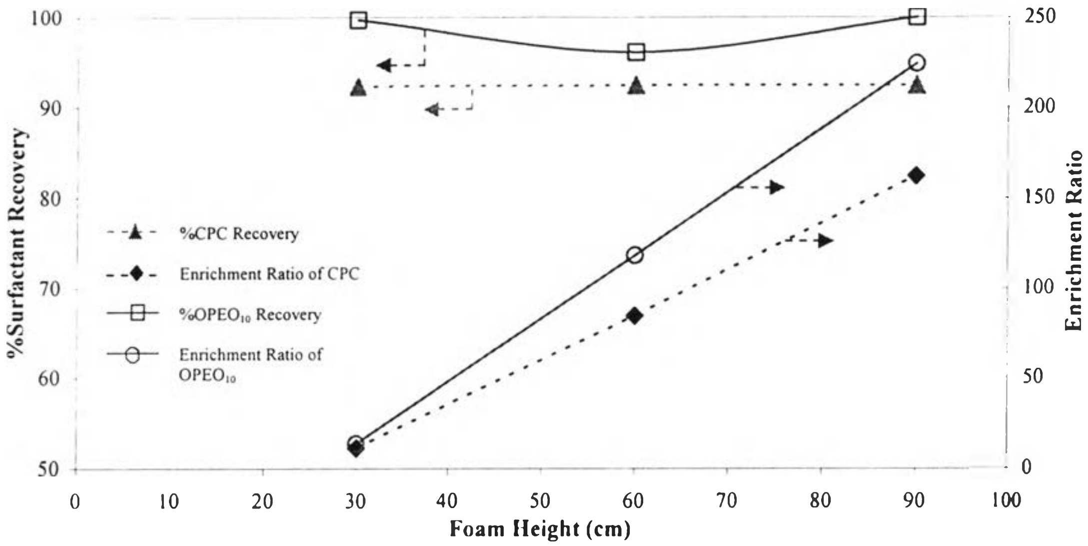

**Figure 4.29** Effect of foam height on separation efficiencies of each surfactant of 3:1 mixed surfactant system under operational conditions of molar ratio of CPC to $OPEO_{10}$ = 3:1, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and feed flow rate = 50 mL/min.

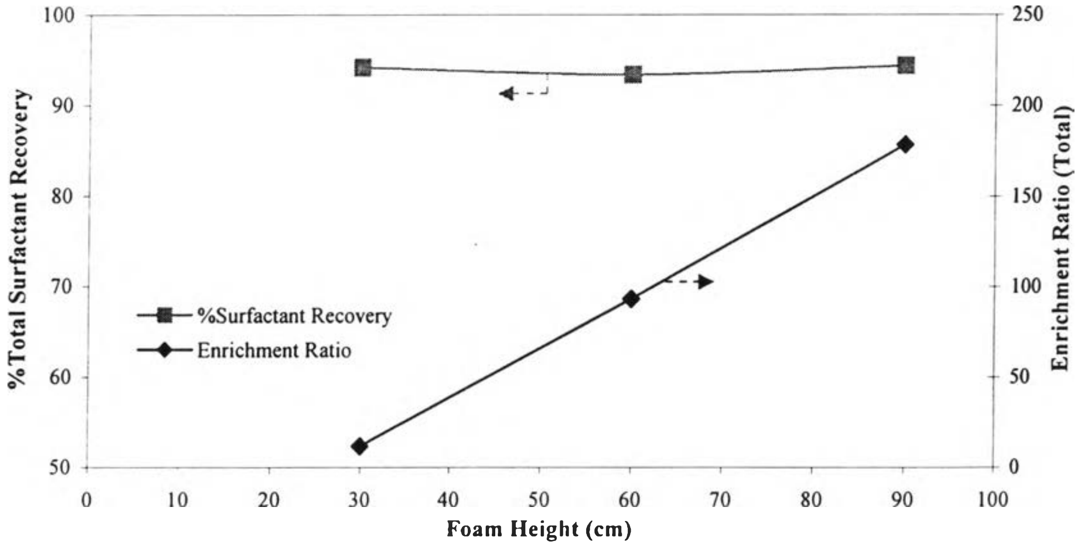

**Figure 4.30** Effect of foam height on total surfactant separation efficiencies of 3:1 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 3:1, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and feed flow rate = 50 mL/min.

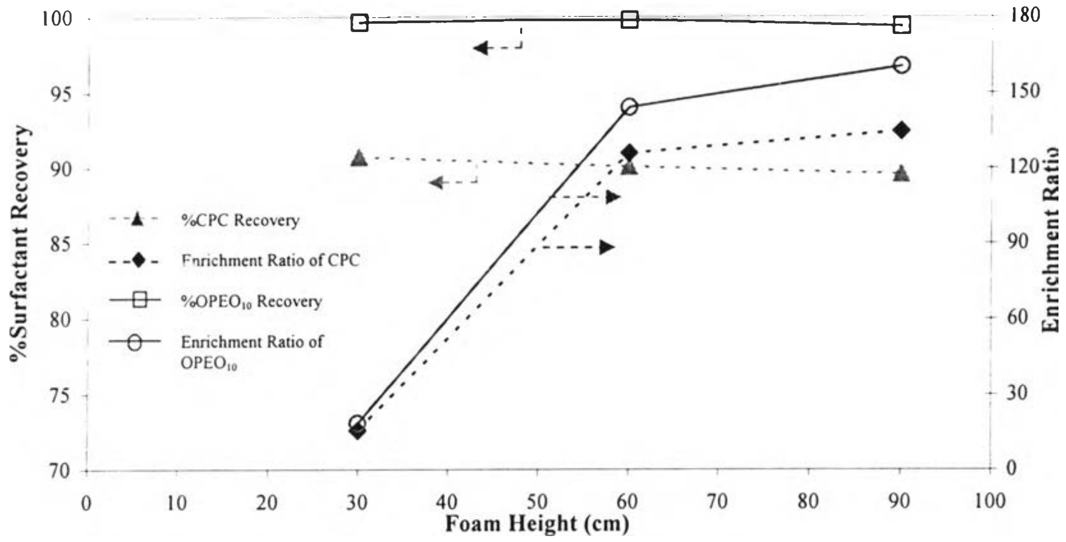

**Figure 4.31** Effect of foam height on separation efficiencies of each surfactant of 1:1 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:1, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and feed flow rate = 50 mL/min.

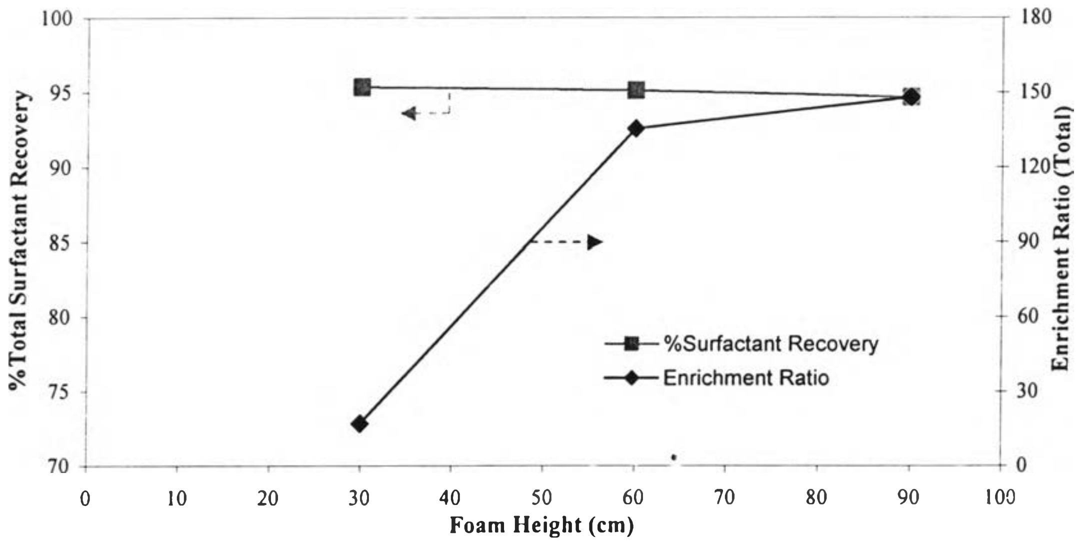

**Figure 4.32** Effect of foam height on total surfactant separation efficiencies of 1:1 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:1, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and feed flow rate = 50 mL/min.

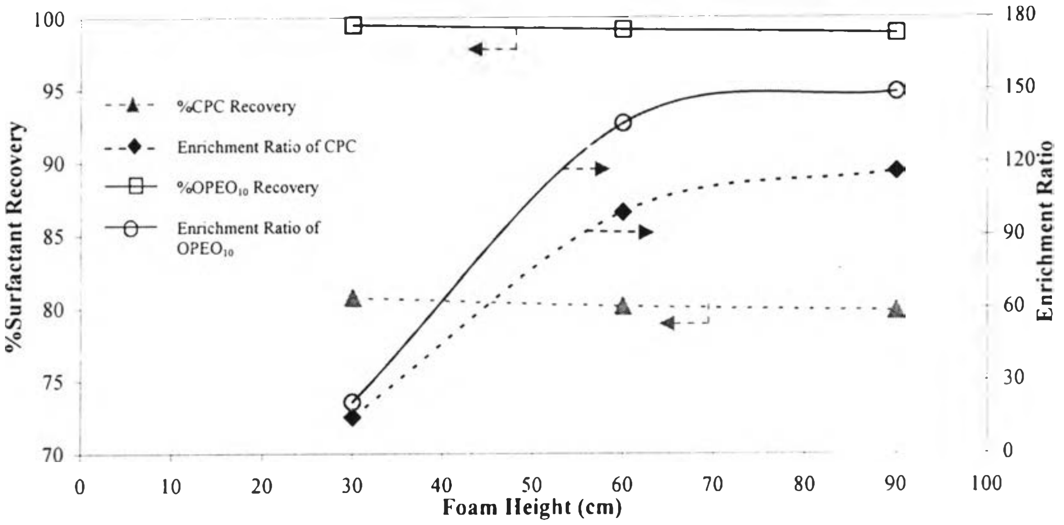

**Figure 4.33** Effect of foam height on separation efficiencies of each surfactant of 1:3 mixed surfactant system operated at molar ratio of 1:3, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and feed flow rate = 50 mL/min.

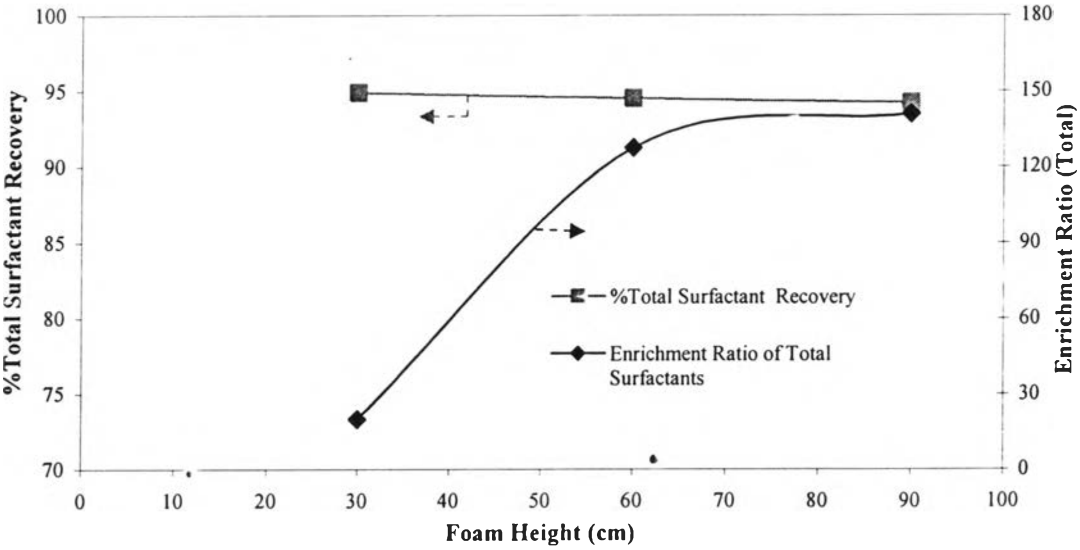

**Figure 4.34** Effect of foam height on total surfactant separation efficiencies of 1:3 mixed surfactant system operated at molar ratio of CPC to $OPEO_{10}$ = 1:3, [total surfactants] = 0.225 mM, air flow rate = 80 L/min and feed flow rate = 50 mL/min.

### 4.6.4 Effect of Feed Molar Ratio

Figures 4.35 and 4.36 show the separation efficiencies of each surfactant and total surfactants in the mixed surfactant systems having three different molars ratio of CPC:OPEO$_{10}$ (3:1, 1:3, and 1:1) compared with the pure CPC and OPEO$_{10}$ systems. It can be seen that the OPEO$_{10}$ recovery received from mixed surfactant systems are higher than that received from pure OPEO$_{10}$ system. This is because the foam stability of all mixed surfactant systems is greater than that of the pure surfactant system as shown in Figure 4.15. The more foam stability, the more repulsive interaction between two layers of the lamellae. For mixed surfactant systems, the more repulsive interaction, the more difficult of foam to collapse, thus OPEO$_{10}$ can be adsorbed on the lamellae film and not leaked when compared to the pure OPEO$_{10}$ system. When considered all the mixed surfactant systems, the surfactant recovery of the mixed surfactant system having a molar ratio of CPC to OPEO$_{10}$ of 3:1 was lower than those of ratio 1:1 and 1:3. Possibility explanation is that the foam ability of 3:1 ratio systems was lower than those of ratio 1:1 and 1:3 as seen in Figure 4.16. Lower foam ability results in having lower foam to be formed, thus led to the lower %surfactant recovery. In contrast, the CPC recovery decreased with an increased amount of OPEO$_{10}$. This can be explained that a high amount of OPEO$_{10}$ added, OPEO$_{10}$ adsorption becomes more competitive resulting in lowering CPC adsorption onto the air/liquid interface of foam. Consequently, the CPC recovery decreases. However, the synergism of OPEO$_{10}$ on the recovery of CPC was found at the 1:3 ratio systems as seen in Figure 4.37. Figure 4.37 show a comparison between the surfactant recovery of CPC or OPEO$_{10}$ from pure system and those from mixed-system. It can be seen that the CPC recovery received from 1:3 ratio systems is not decreased as same as in single system but it seems to increase and close to the recovery of CPC in single system. The possibility is that the 1:3 ratio gave the highest foam ability. A higher foam ability results in having more foam to be formed, thus led to the higher %surfactant recovery. When comparing the enrichment ratio of CPC or OPEO$_{10}$ in single and mixed surfactant system, it can be seen from Figure 4.35 and 4.38 that the enrichment ratio of both CPC and OPEO$_{10}$ obtained from mixed surfactant system is lower than those obtained from pure surfactant system. This may be explained by the foam stability of surfactant solution as seen in Figure

4.15. The foam stability of mixed surfactant systems is higher than that of pure surfactant system. The more foam stability, the lower drainage rate of water from foam explains the lower enrichment ratio of mixed surfactant systems.

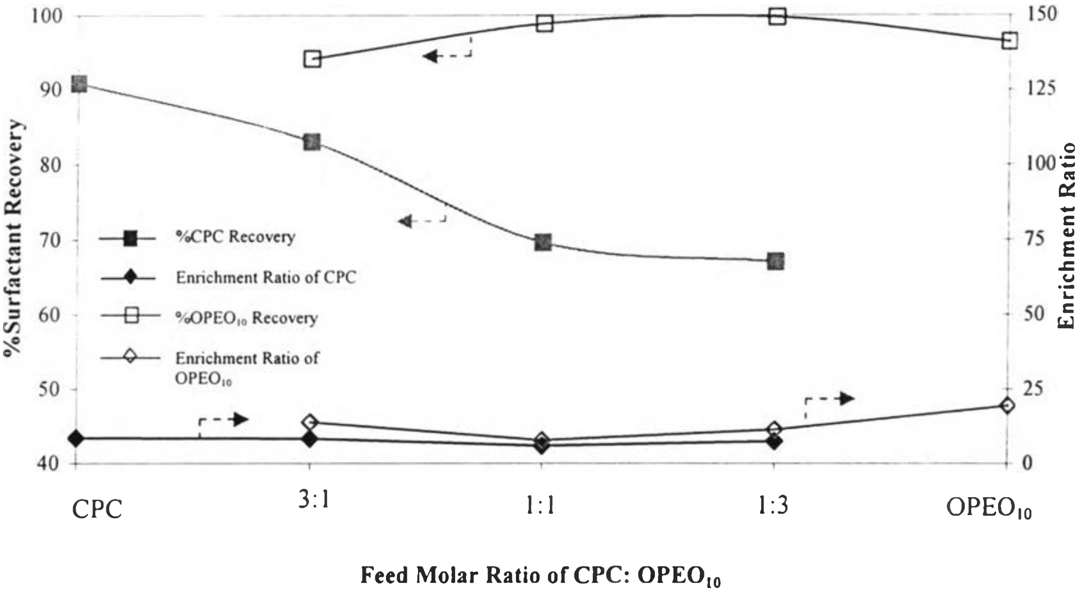

**Figure 4.35** Effect of feed molar ratio of CPC to OPEO$_{10}$ on separation efficiencies of each surfactant operated at [total surfactants] = 0.225 mM, air flow rate = 60 L/min and feed flow rate = 100 mL/min.

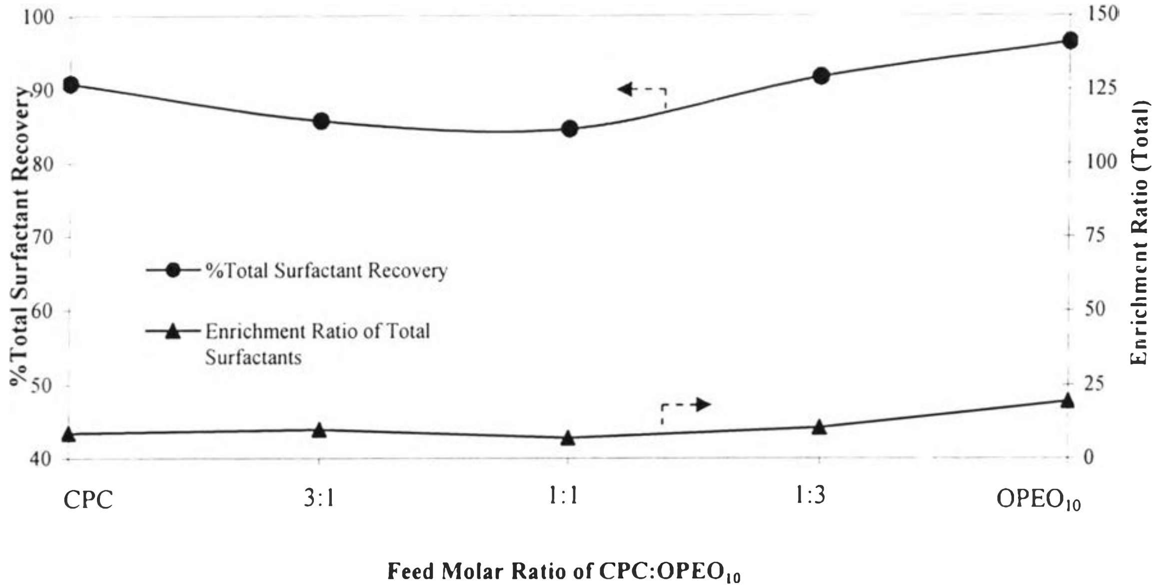

**Figure 4.36** Effect of feed molar ratio of CPC to OPEO$_{10}$ on total surfactant separation efficiencies operated at [total surfactants] = 0.225 mM, air flow rate = 60 L/min and feed flow rate = 100 mL/min.

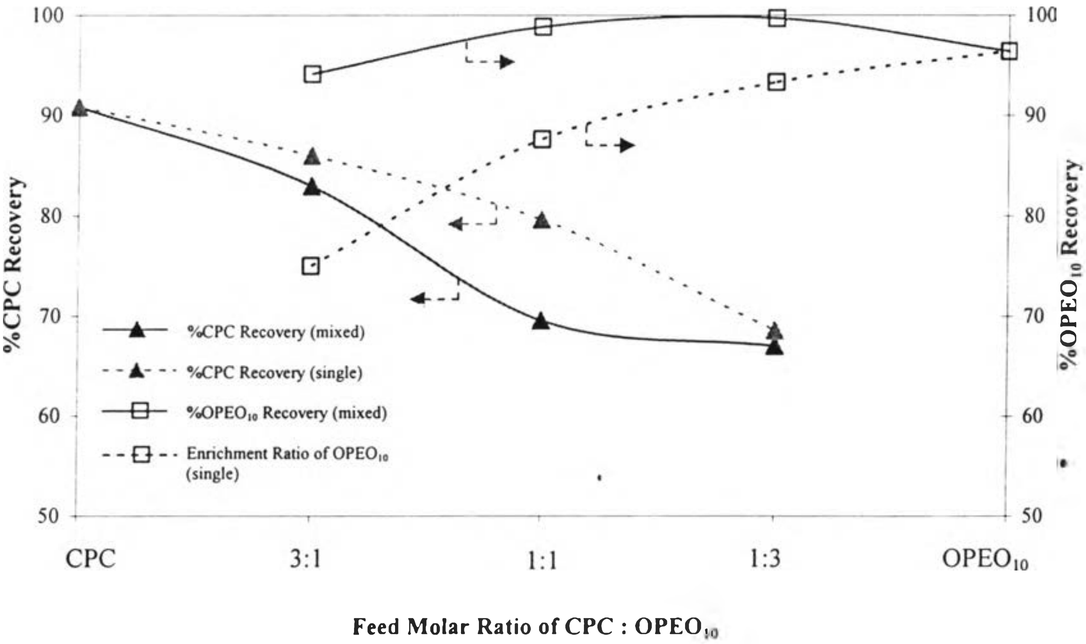

**Figure 4.37** Comparison of each surfactant recovery between single-surfactant systems and mixed-surfactant systems operated at air flow rate = 60 L/min, feed flow rate = 100 mL/min and [total surfactants] = 0.225 mM.

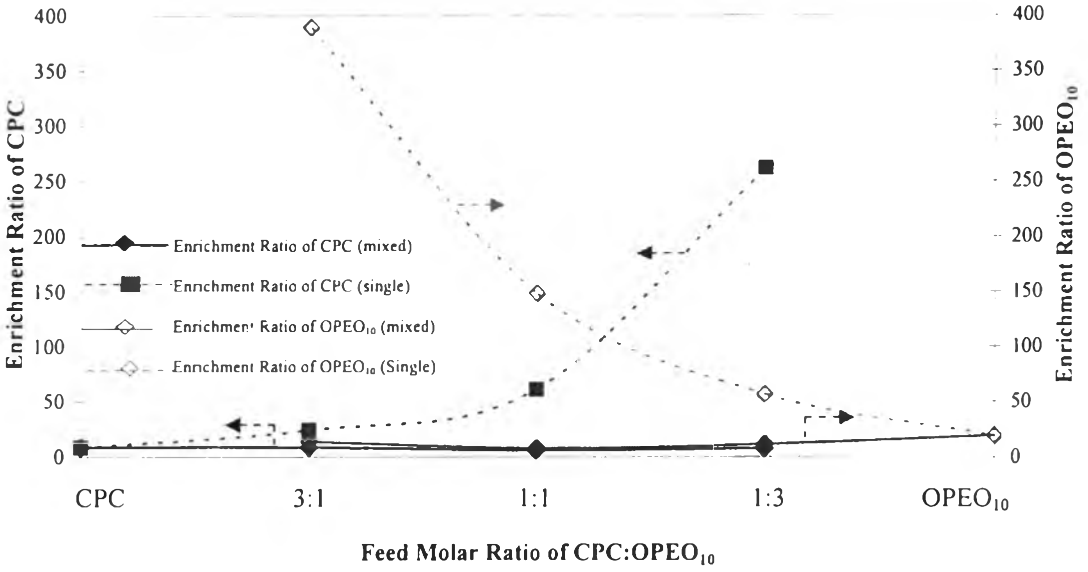

**Figure 4.38** Comparison of each surfactant enrichment ratio between single-surfactant systems and mixed-surfactant systems operated at [total surfactants] = 0.225 mM, air flow rate = 60 L/min and feed flow rate = 100 mL/min.