CHAPTER IV
RESULTS AND DISCUSSION

4.1 Phase Behaviors

As mentioned before, the objective of this study was to investigate the relationship between the efficiency of froth flotation and the ultralow interfacial tension (IFT) of wastewater containing diesel. Alfoterra 145-5PO (Branch alcohol propoxylated sulfate, sodium salt) was used to form microemulsions with diesel because Alfoterra has a proper HLB for diesel-water system and is expected to form middle phase microemulsions. The effects of surfactant concentration, NaCl concentration, and oil to water ratio on IFT of diesel were studied.

Pondstabodee *et. al.* (1998) concluded that the highest removal of ortho-dichlorobenzene (ODCB) of froth flotation corresponded to the formation of Winsor Type III microemulsions. In addition, Chavadej *et. al.* (2003) discovered that most of oil removed came from the excess oil phase, not from the middle phase in a Winsor type III microemulsion system. Therefore, in this study, it is also hypothesized that the ultralow IFT which is one of the unique characteristics of Winsor Type III microemulsions can enhance the efficiency of froth flotation.

In this study, the microemulsion formation of diesel with Alfoterra showed only two obvious phases, which were the water and oil excess phases. The layer of the middle phase was very thin, and it could not be clearly observed visually. Consequently, the measurement of the phase transformation became difficult to identify whether the system had a middle phase or not. Hence, the phase diagram of diesel with Alfoterra is not shown here. The IFT of the system was measured by the spinning drop tensiometer to examine the existence of Winsor Type III microemulsions. The diagrams of IFT as a function of surfactant concentration, salinity, and oil to water ratio are illustrated here.

4.1.1 Effect of Single Surfactant Concentration on IFT

Figure 4.1 illustrates the effect of single surfactant concentration on IFT at 5 wt% salinity and an oil to water initial volumetric ratio of 1:1.

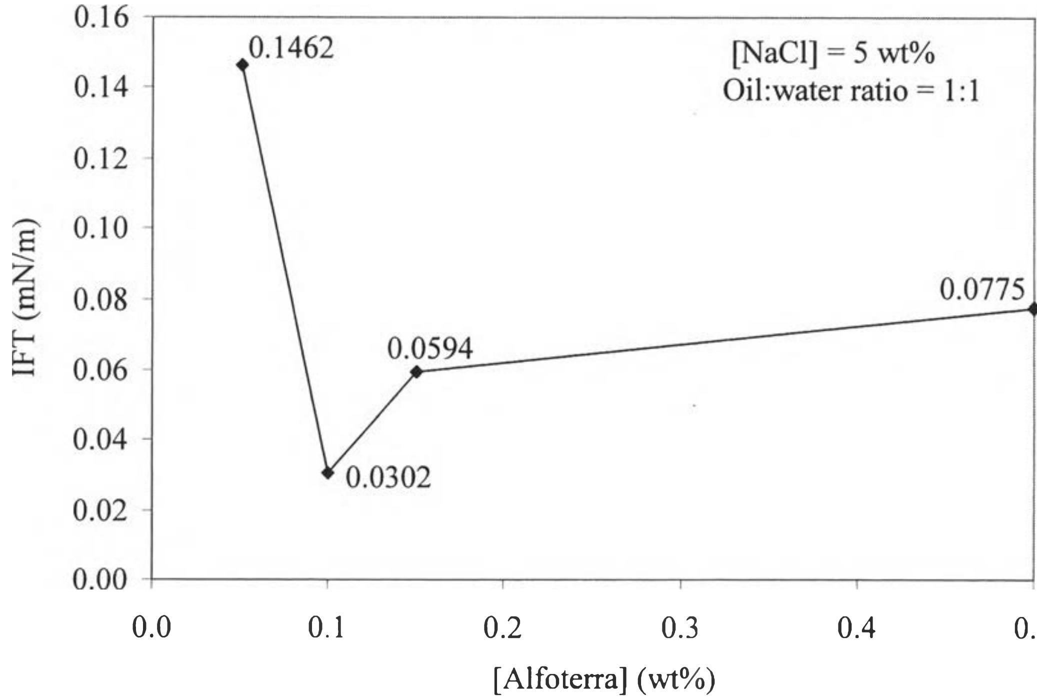

Figure 4.1 IFT as a function of Alfoterra concentration at 5 wt% of NaCl with oil to water ratio = 1:1 (v:v), and 30 °C.

From Figure 4.1, the IFT of the system decreases rapidly when Alfoterra concentration increases from 0.05 to 0.10 wt%. And then, it increases gradually with the increase in the Alfoterra concentration from 0.10 to 0.5 wt%. This is because the repulsive force between the anionic head groups of Alfoterra increases with the increase in the Alfoterra concentration. Therefore, micelle is difficult to form leading to lower oil solubilization, but higher IFT as shown by Equation (4.1), Chun-Huh's equation.

$$\gamma \ \alpha \ SP^{-2} \qquad (4.1)$$

where; γ = interfacial tension, SP = solubilization parameter

The minimum IFT around 3.025 x 10^{-2} mN/m was found at 0.10 wt% of Alfoterra is considered to be in the range of the ultralow IFT (10^{-2}-10^{-3} mN/m) which is typically observed in a system with the middle phase microemulsion formation. Consequently, it can be concluded that the phase behavior study of the diesel system by using Alfoterra as a surfactant can form the middle phase or Winsor Type III microemulsion.

4.1.2 Effect of Mixed Surfactant Concentration on IFT

Since the microemulsion systems of diesel with pure Alfoterra had very poor foam formation, it was not possible to run froth flotation experiments. Consequently, adding SDS as another frother to the solution was introduced because it provides good foamability and foam stability. The composition of Alfoterra was fixed at 0.1 wt% because it provides the minimum IFT. The SDS concentration was varied from 0.1, 0.5, 0.7, and 1 wt% with 3 wt% NaCl and an oil to water initial volumetric ratio equal to 1:19. As shown in Figure 4.2, an increase in SDS concentration increases the IFT and the minimum IFT appears at 0.1 wt% SDS (0.2866 mN/m). This is because SDS possesses a linear structure and a high HLB value which is difficult to form Winsor Type III microemulsions with diesel, high hydrophobic oil, leading to IFT. In contrast, Alfoterra possesses a hydrpphobic branch structure and a low HLB value which can form a Winsor Type III microemulsion easily with diesel.

4.1.3 Effect of NaCl Concentration on IFT of Single and Mixed Surfactant Systems

The effect of adding salt on the IFT was studied in both single (Alfoterra) and mixed surfactant (Alfoterra and SDS) systems with salinity scan.

4.1.3.1 IFT with Single Surfactant System

Figure 4.3 shows IFT as a function of NaCl concentration or salinity scan at 0.1 wt% of Alfoterra, and an oil to water ratio of 1:1. From the result, the minimum IFT was found at 5 wt% NaCl concentration. At free-NaCl concentration, the repulsive force between anionic head groups is high leading to a very low aggregation number and a very small size of micelles, so the amount of solubilized

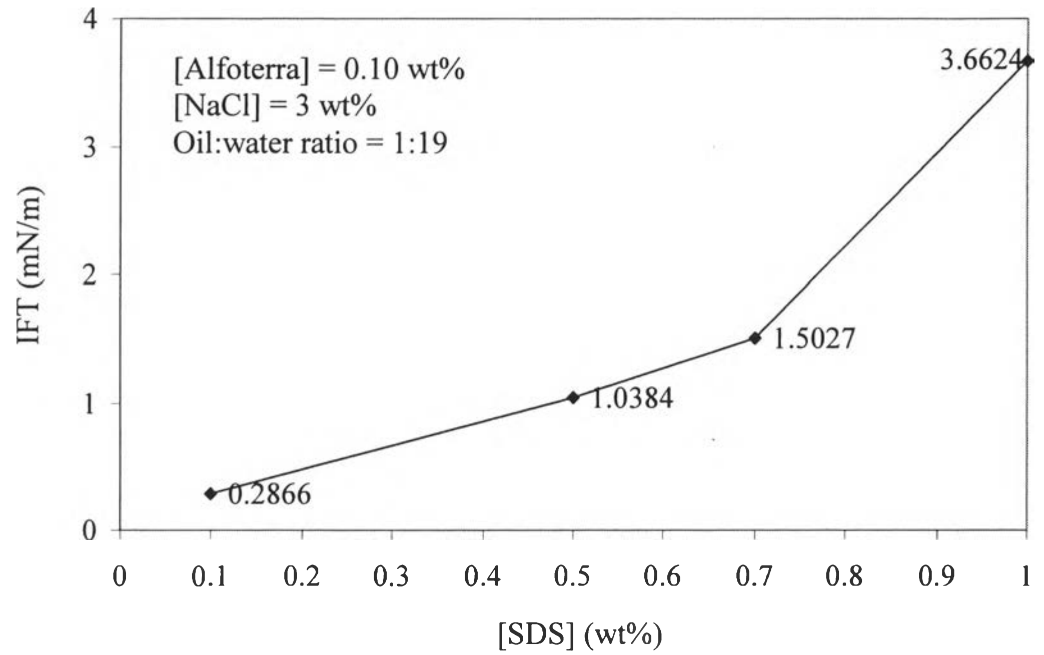

Figure 4.2 IFT as a function of SDS concentration at 0.1 wt% Alfoterra, 3 wt% NaCl, an oil to water ratio = 1:19, and 30 °C.

oil in the inner core of micelles is low resulting in a high IFT value. When NaCl is added into the system, it reduces the repulsive force between anionic head groups resulting in increasing aggregation number, so the amount of solubilized oil into the inner core micelles increases leading to the reduction of IFT. At very high NaCl concentrations, the charge at the head group of surfactants is neutralized, so the distance among surfactant molecules in the micelle become very close resulting in lowering aggregation number, so the amount of solubilized oil in the inner core of micelle is low leading to higher IFT.

4.1.3.2 IFT with Mixed Surfactant System

The result from the effect of single surfactant concentration on IFT shows that 0.1 wt% of Alfoterra provides the minimum IFT. In addition, the result from the effect of SDS concentration in the mixed surfactant system on the performance of froth flotation shows that 0.5 wt% of SDS provides the best performance of the froth flotation.

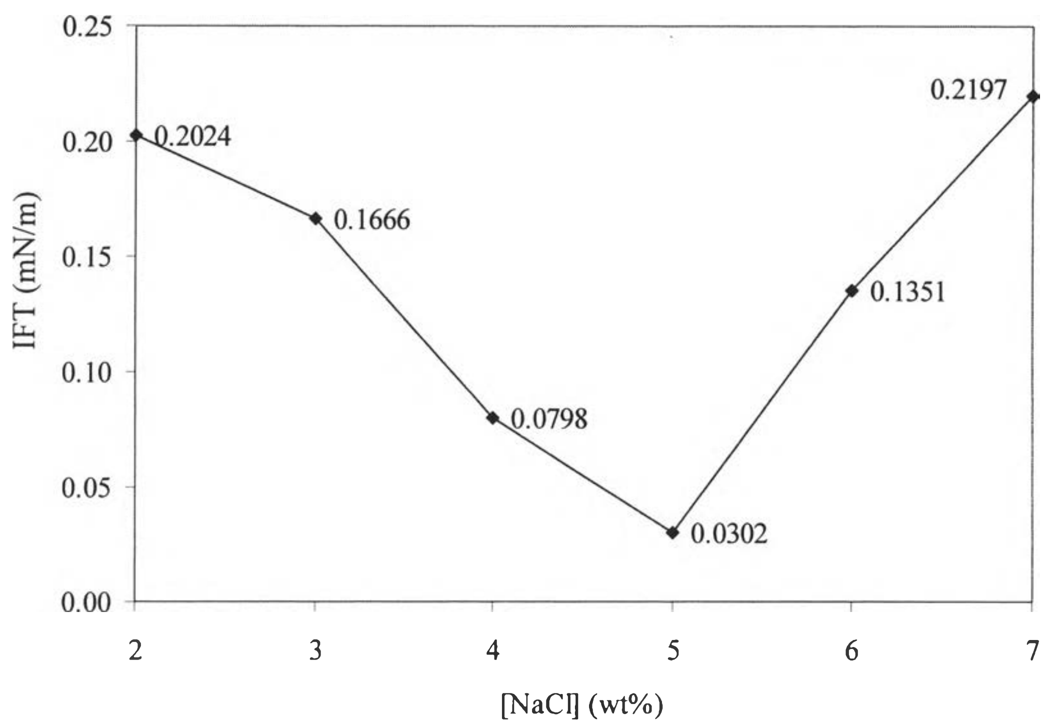

Figure 4.3 IFT as a function of salinity at 0.1 wt% of Alfoterra, and an initial oil to water ratio = 1:1 (v:v).

Consequently, the mixed surfactant system of 0.1 wt% of Alfoterra and 0.5 wt% of SDS was used for the IFT measurement with salinity scan in the range of 2 to 4 wt% of NaCl. A higher NaCl concentration than 4 wt% was not considered because foamability and foam stability of the system are very poor, so froth flotation could not be operated as illustrated in Figures 4.4 and 4.5. The IFT of the mixed surfactant system as a function of salinity with an initial oil to water ratio equal to 1:1 is illustrated in Figure 4.6. From the figure, as NaCl concentration increases from 2 to 4 wt%, the IFT decreases almost linearly. This is because the repulsive force between the anionic head groups of both Alfoterra and SDS decreases when the NaCl concentration increases leading to an increase in the aggregation number as well as increasing solubilization of oil into the inner core of micelles causing the decrease in the IFT. In other words, an increase in salinity enhance the phase transformation of a Winsor Type I microemulsion toward a Winsor Type III microemulsion.

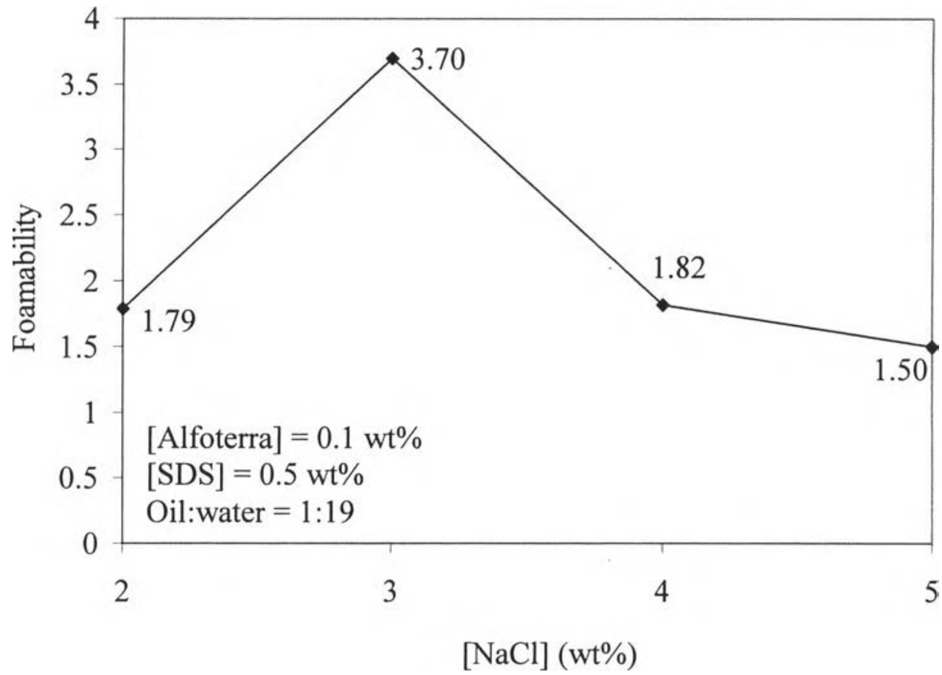

Figure 4.4 Foamability of mixed surfactant system at different NaCl concentration.

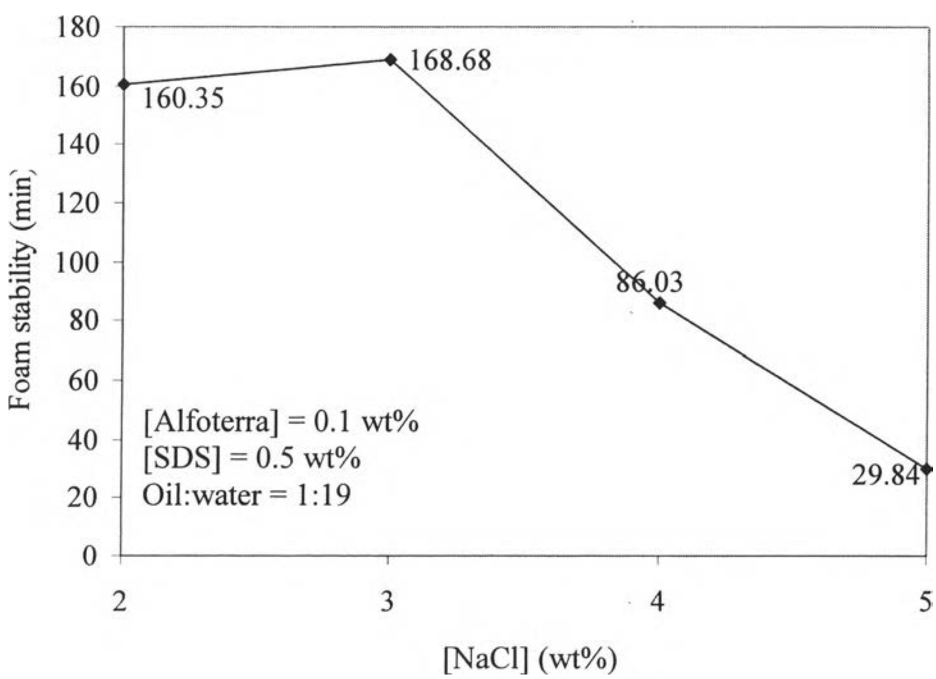

Figure 4.5 Foam stability of mixed surfactant system at different NaCl

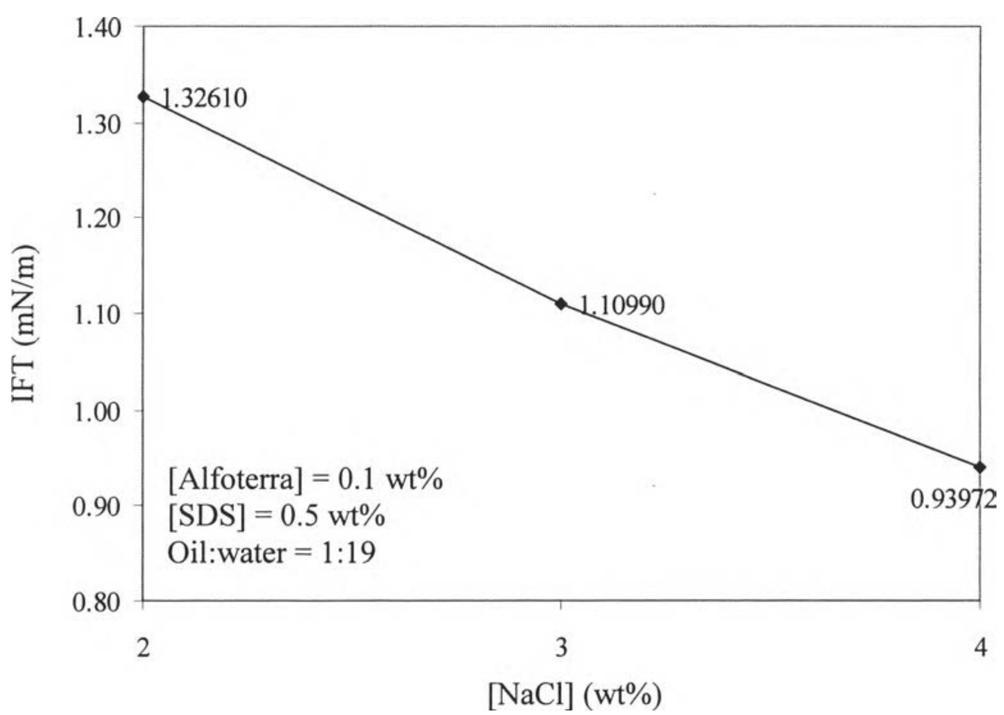

Figure 4.6 IFT of the mixed surfactant system as a function of salinity with an initial oil to water ratio = 1:19 (v:v).

4.1.4 Effect of Oil to Water Ratio on IFT

As mentioned before, the optimum NaCl concentration of 4 wt% provides a relatively low IFT and reasonably high foamability and foam stability, and so 4 wt% NaCl was selected to study the effect of oil to water ratio on the IFT. Figure 4.7 illustrates IFT as a function of oil to water ratio with 0.1 wt% of Alfoterra, 0.5 wt% of SDS and 4 wt% of NaCl. It was found that the IFT seems to be independent on the oil to water ratio. This may be due to the same solubilization power of each sytem because it contains nearly the same Alfoterra and SDS concentration as well as NaCl concentration.

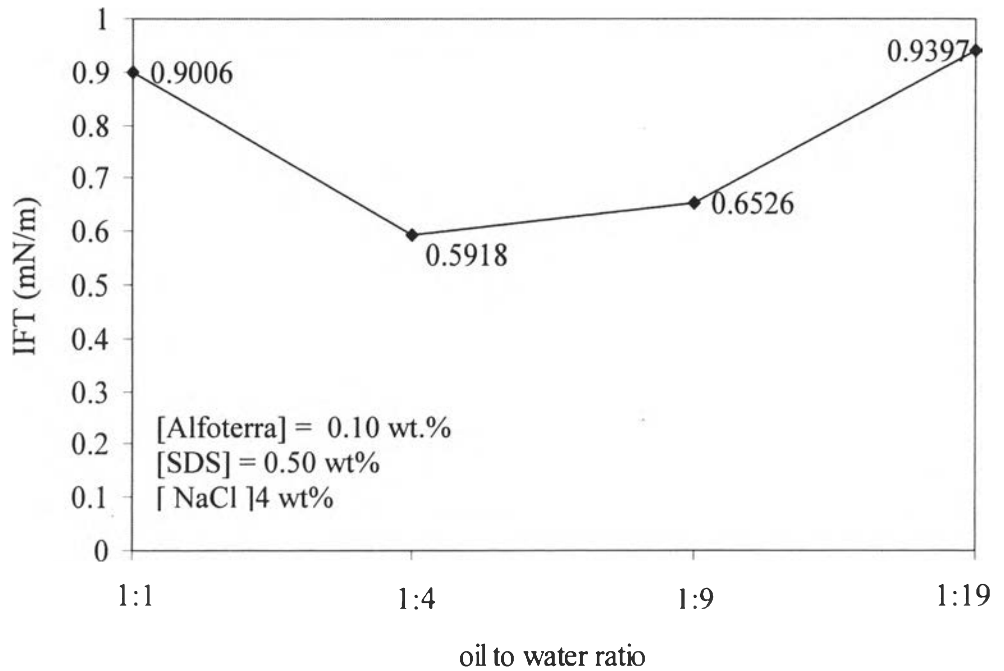

Figure 4.7 IFT as a function of oil to water ratio at 0.1 wt% Alfoterra, 0.5 wt% SDS, and 4 wt% NaCl.

4.2 Froth Flotation Performance

Oil removal and enrichment ratio are significant parameters to indicate the performance of froth flotation process. In addition, the surfactant removal, foam wetness, and foam flow rate should be determined and used for froth flotation performance evaluation.

Generally, high oil removal efficiency is a vital requirement for an effective froth flotation process but it is not the sole factor. If oil and water are present in the froth with the same propotion as in the influent, the selectivity and separation of oil from water do not occur. Hence, for effective separation, the concentration of oil in the overhead froth has to be much higher than that in the feed. Consequently, in this study, the separation efficiency is indicated by the enrichment ratio, which is defined as the ratio of concentration of oil in the overhead froth to that in the feed. In order to achieve the separation, the enrichment ratio must be greater than one. Moreover, the higher the enrichment ratio, the better the separation is. A total surfactant removal represents the amount of both Alfoterra and SDS that can remove from the solution.

4.2.1 Effect of Single Surfactant Concentration on Performance of Froth Flotation

Figure 4.8 shows that the oil removal decreases with time of the froth flotation unit with continuous mode of operation. This is because as the solution is agitated longer, foam stability decreases due to the decrease in the oil droplet size, but still higher than 2-10 μm. Because of a speed using in this research is 2000 rpm, but the speed that can reduce the oil droplet size to 2-10 μm must be controlled at 5000-10000 rpm (Jarudilokkul *et al.*, 2003). The dependence of stability on the oil drop size can be explained by the oil accumulation mechanism. The smaller droplets tend to accumulate in the plateau borders of foam lamella at a lesser extent owing to their size and buoyancy force; therefore, they have less resistance for the movement in the plateau borders of foam lamella (Schramm, 1992). Consequently, they are less likely to be trapped within the plateau borders. As the drop size decreases, the accumulation of oil decreases. Nevertheless, the viscosity of emulsions increases rapidly with decreasing drop size under the range of 1-2 μm due to the interaction between the oil drops becomes significant. Hence, in the presence of very fine emulsion, the liquid drainage is much slower, and thus the foam stability is much greater. The foam stability can be increased by having small oil drop size in the range of 1-2 μm. This phenomena can be explained by the effect of size of droplets as mentioned before. However, reducing size of oil droplets into the range of 1-2 μm is very difficult and not commercially practical. Hence, an addition of a frother to the solution was selected to solve this problem. Figure 4.9 compares the foam stability of agitated-solution and non-agitated solution systems with different Alfoterra concentrations. The non-agitated system was found to provide higher foam stability than that of the agitated-system.

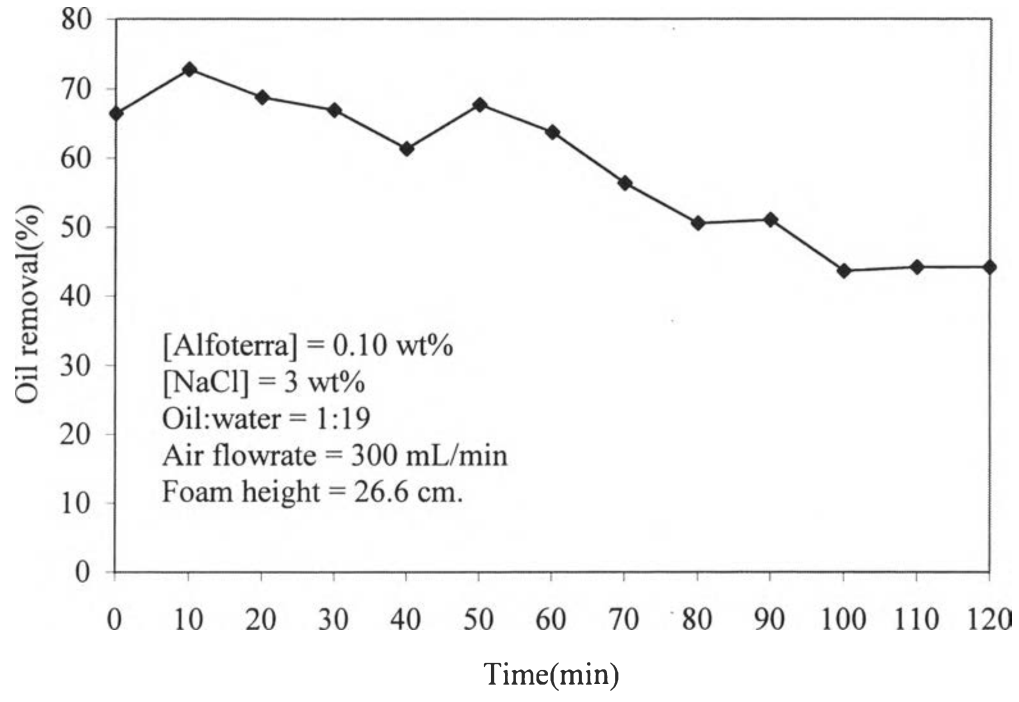

Figure 4.8 Dynamic oil removal of continuous froth flotation unit operated at 0.10 wt% Alfoterra, 3 wt% NaCl, oil:water ratio = 1:19, air flow rate = 300 mL/min, and foam height = 26.6 cm, and hydraulic retention time = 67 min.

4.2.2 Effect of Mixed Surfactant Concentration

According to the results from the batch operation, 0.1 wt% of Alfoterra and 3 wt% of NaCl provides good performance for froth flotation. Therefore, this condition was selected to run the froth flotation in the continuous mode of operation. From the previous study (Withayapanyanon, 2003), it has been proposed that the ultralow IFT of the Winsor Type III microemulsion is not the sole factor affecting the flotation process. Foamability and foam stability are other parameters influencing oil removal efficiency in the froth flotation process.

According to the result from the effect of agitation on the performance of the froth flotation, the oil removal decreases as the solution is further agitated. In order to improve the efficiency of the froth flotation operation, SDS was added together with Alfoterra because SDS provides good foamability and foam stability.

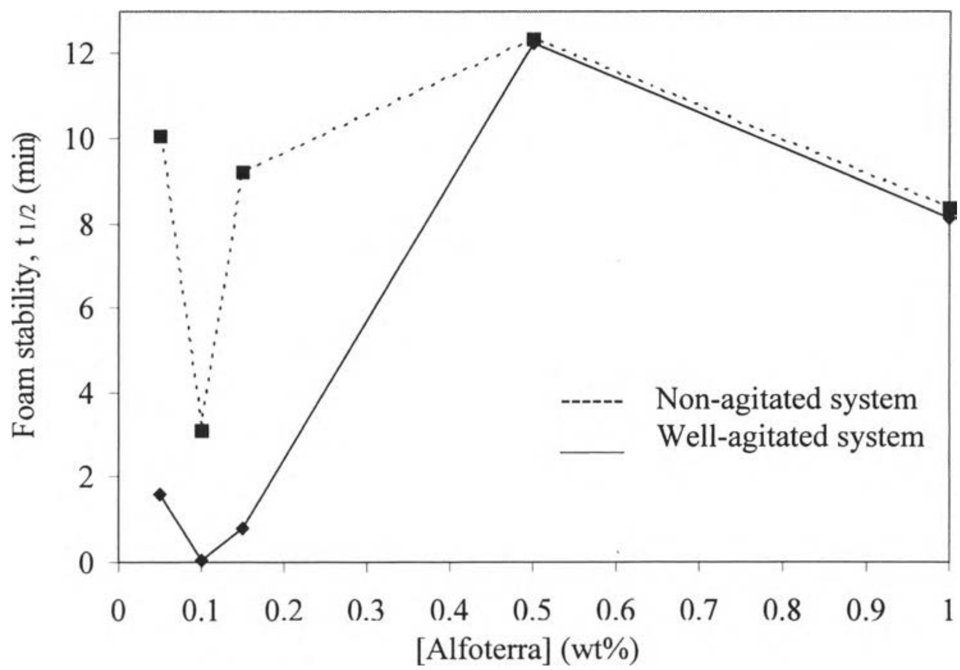

Figure 4.9 Foam stability of single system at different Alfoterra concentrations when (NaCl concentration = 3 wt%, and oil:water ratio = 1:19 between the non-agitated system and the well-agitated system with speed 2000 rpm for 1 hour).

4.2.2.1 Effect of SDS Concentration in Mixed Surfactant System on Performance of Froth Flotation

As shown in Figure 4.10, for the SDS concentrations in the range from 0.1 to 0.5 wt%, the oil removal increases because there are more foam to be produced with increasing surfactant concentration (see Figure 4.11). Therefore, the surfactant can carry oil and remove it from the solution more efficiently. When the SDS concentration further increased to 0.7 wt%, the oil removal decreased. A possible explanation for this is the foamability effect. Figure 4.12 illustrates the effect of SDS concentration on foamability of the system. As SDS concentration increases from 0.5 to 0.7 wt%, the foamability decreases slightly. This may be because at a high SDS concentration, there is more water in the foam lamellae also known as wet foam. Consequently, foam with a higher SDS concentration is heavier than that with lower SDS concentration leading to the collapse of foam much easier. When the SDS concentration further increases to 1 wt%, the oil removal increases again because the rate of foam generation increases as shown in Figure 4.13. Even though the increasing SDS concentration increases the thickness of foam lamella leading to the collapse of foam, there is a more easily balance between the ability of foam formation due to the high concentration of surfactant and the foam collapse due to the wet foam.

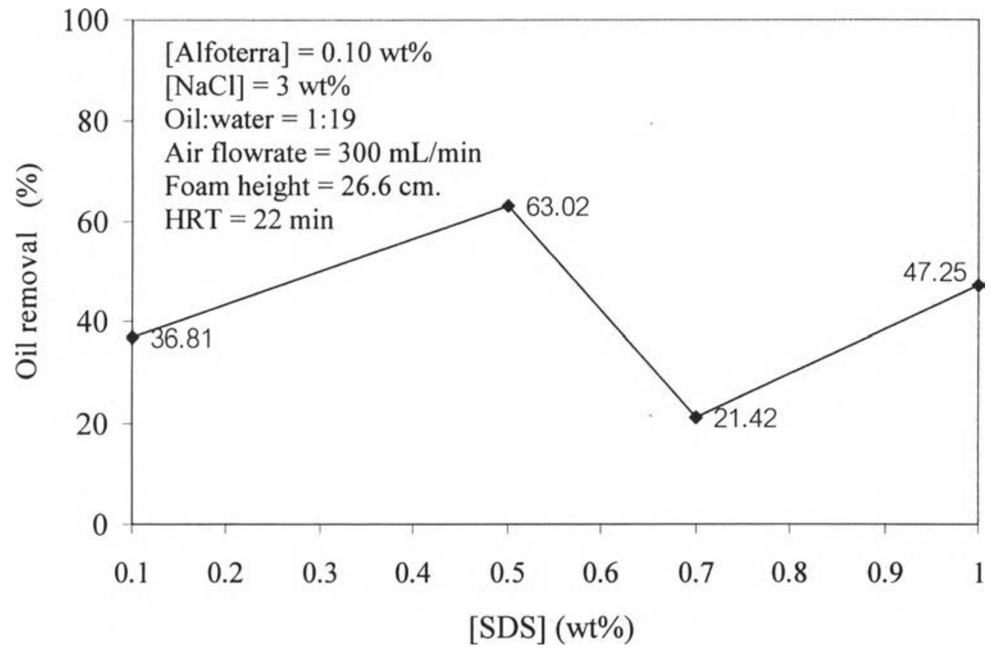

Figure 4.10 Oil removal efficiency of mixed surfactant system at different feed SDS concentrations.

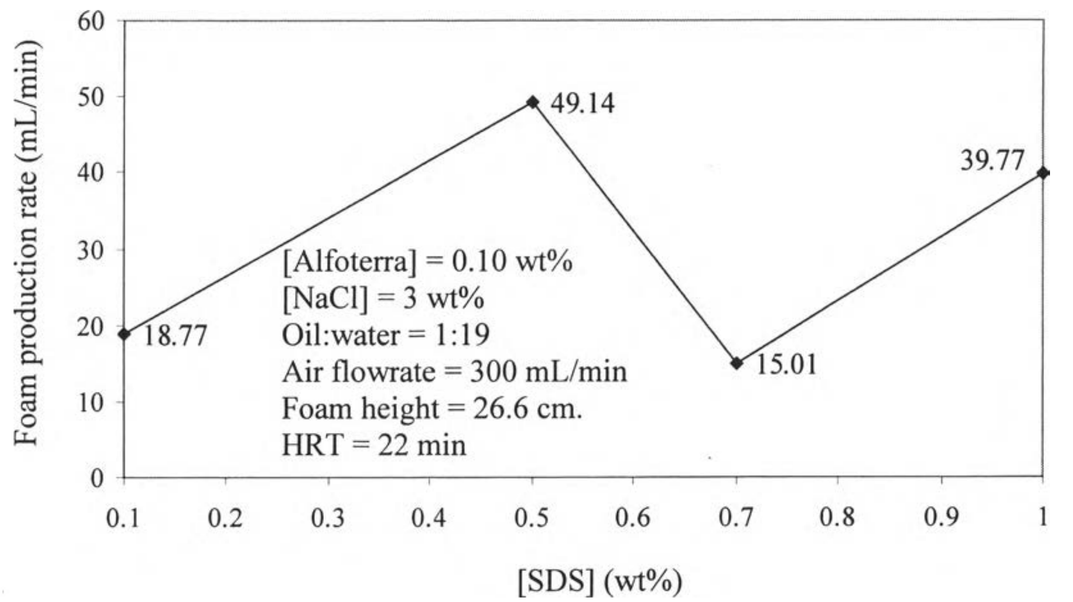

Figure 4.11 Foam production flow rate of mixed surfactant system at different feed SDS concentrations.

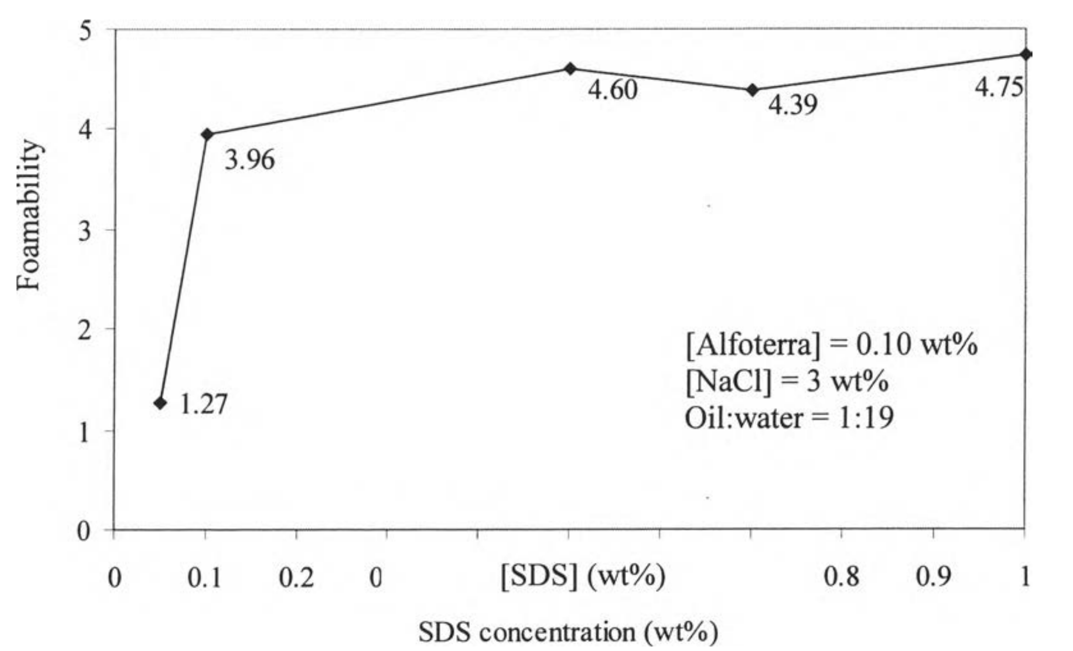

Figure 4.12 Foamability of mixed surfactant system at different feed SDS concentrations.

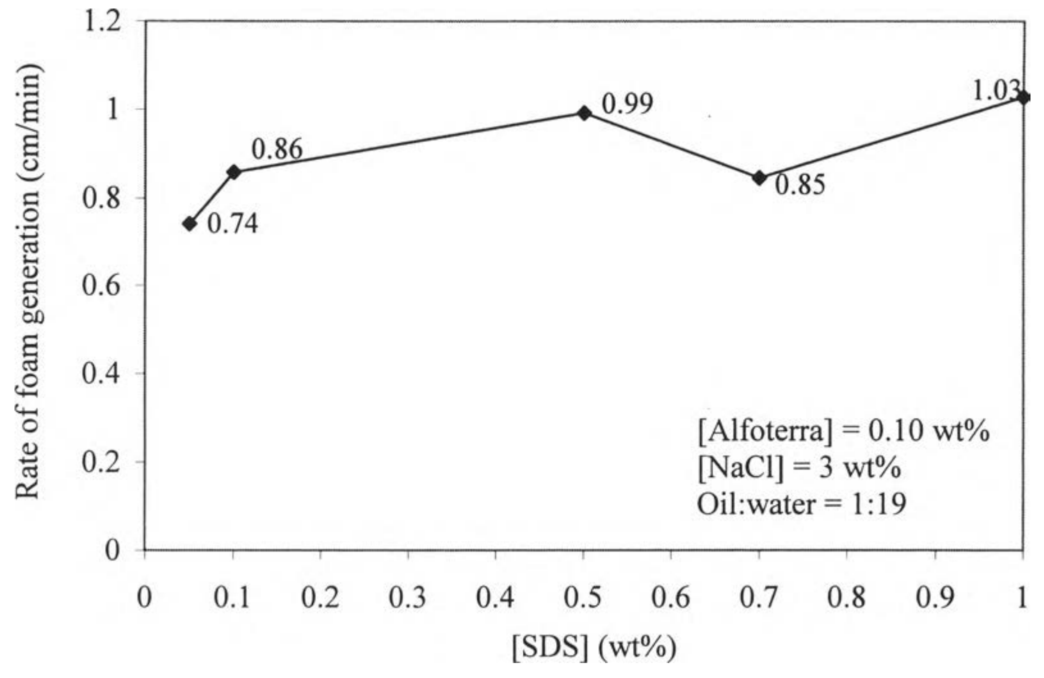

Figure 4.13 Rate of foam generation of mixed surfactant system at different feed SDS concentrations.

The effect of mixed surfactant concentration on the enrichment ratio of diesel is shown in Figure 4.14. As the SDS concentration increases from 0.1 wt% to 0.5 wt%, the enrichment ratio slightly decreases because the concentration of surfactant at the foam decreases with increasing feed SDS concentration. Hence, the foam lamellae of a higher surfactant concentration becomes thicker than that with a lower surfactant concentration leading to a larger amount of water in the foam lamellae, so 0.5 wt% of SDS results in the low enrichment ratio of diesel. However, when the SDS concentration further increases to 0.7 wt% and 1 wt%, the enrichment ratio slightly increases because the foam stability of the system increases with increasing SDS concentration as shown in Figure 4.15. In addition, increasing surfactant concentration increases the hydrophobic region, so the amount of oil content in the foam increases. The combined effect between the increase in the hydrophobic region and the increasing the amount of water in the foam lamellae leads to the insignificant change in the enrichment ratio when SDS concentration increases from 0.7 to 1 wt%. Moreover, this is corresponds to the result of the effect of SDS concentration on the foam wetness because as the increasing SDS concentration from 0.7 to 1 wt% results in an increase in the foam wetness. The profile of the foam wetness (see Figure 4.16) is exactly the same as those of the oil removal and the foam production rate but in contrast to that of the enrichment ratio of oil. The highest foam flow rate and the lowest enrichment ratio were obtained with 0.5 wt% SDS; hence, a high amount of water in the collapsed foam results in the high foam wetness. At the point that lowest foam flow rate and highest enrichment ratio of oil are obtained, the decrease in the foam wetness can be observed because the oil content in the collapsed foam is high.

The effect of SDS concentration on the surfactant removal is shown in Figure 4.17. Increasing SDS concentration from 0.1 to 0.5 wt% results in an increase in the surfactant removal. But when the SDS concentration is further increased to 0.7 wt%, the surfactant removal is decreased. The surfactant removal increases again with 1 wt% SDS concentration. This result relates to the effect of SDS concentration on the oil removal and the foam production rate as shown in Figures 4.10 and 4.11 because when foam production rate increase resulting in the increases of surfactant removal and when the foam production rate decreases leading to the decreases of the surfactant removal also as well as the effect of SDS concentration on the oil removal as described before.

As shown in Figure 4.18, the enrichment ratio of the surfactant decreases when the SDS concentration increases from 0.1 to 0.5 wt% and then slightly increases. This is related to the result of enrichment ratio of oil as shown in Figure 4.14. This reason can be explained as described in the effect of SDS concentration on the enrichment ratio of diesel.

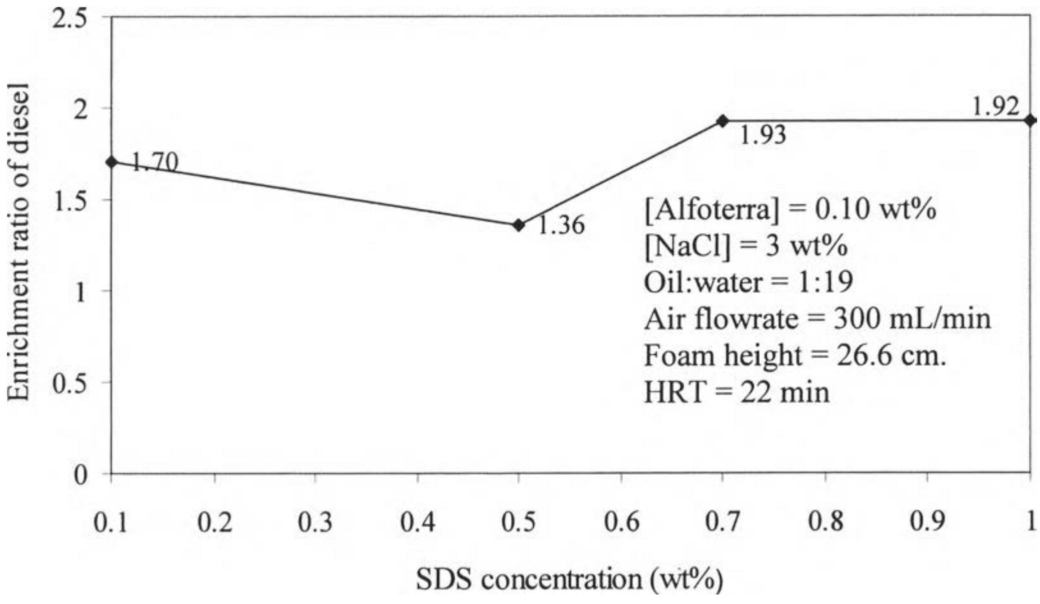

Figure 4.14 Enrichment ratio of mixed surfactant system at different feed SDS concentrations.

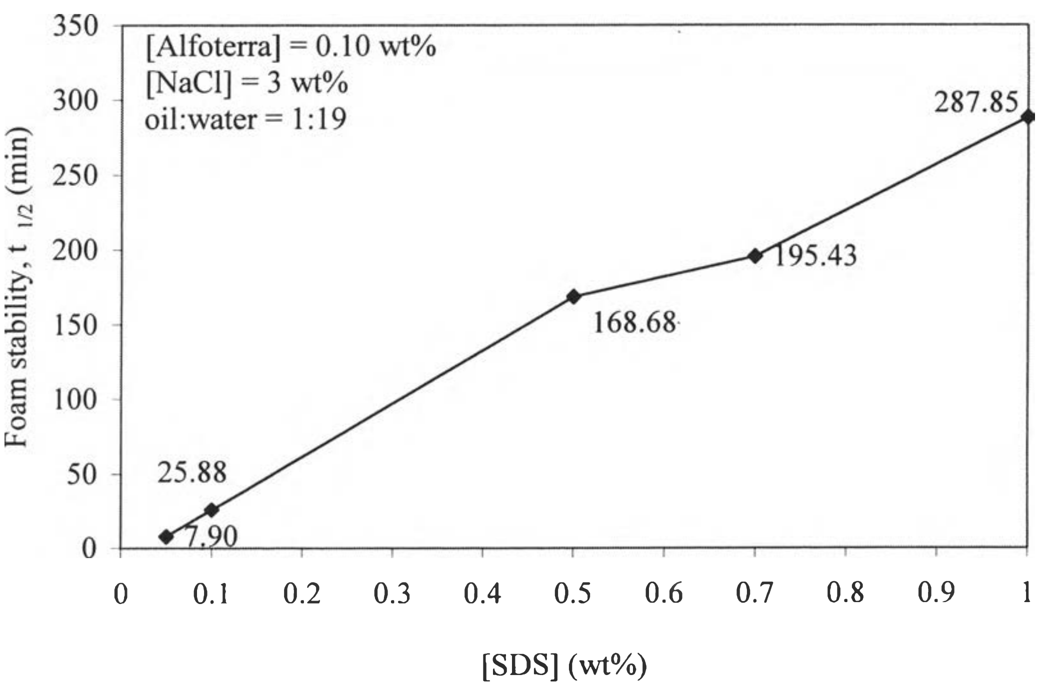

Figure 4.15 Foam stability of mixed surfactant system at different initial SDS concentrations.

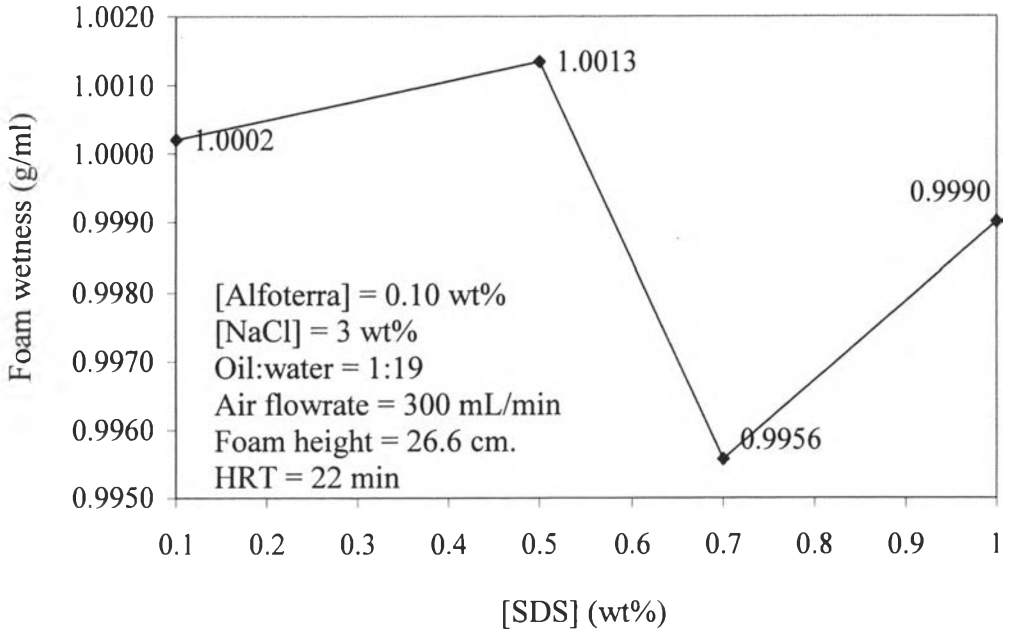

Figure 4.16 Foam wetness of mixed surfactant system at different feed SDS concentrations.

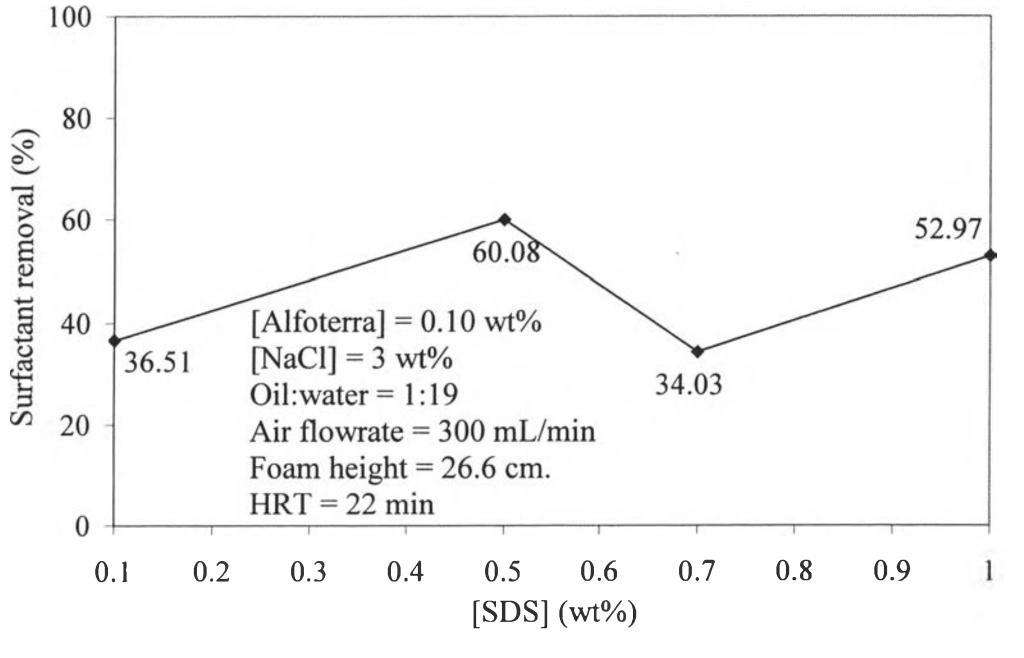

Figure 4.17 Surfactant removal of mixed system at different feed SDS concentrations.

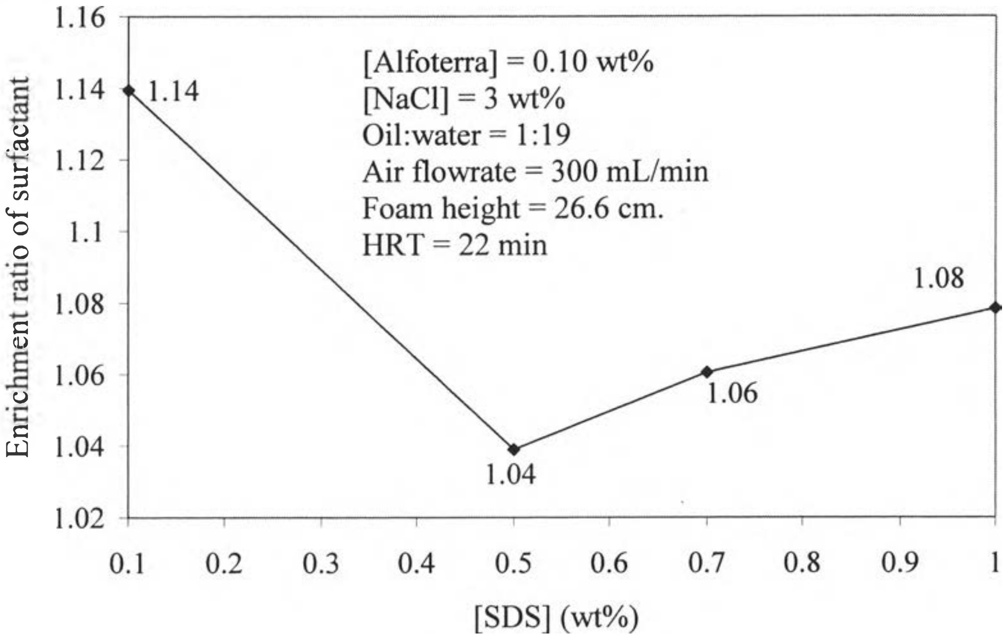

Figure 4.18 Enrichment of surfactant of mixed surfactant system at different feed SDS concentrations.

4.2.3 Effect of NaCl Concentration on Performance of Froth Flotation

It has been known that salinity is one of operational parameters affecting froth flotation operation. The effect of NaCl concentration on the operation of froth flotation was carried out by varing NaCl concentration in the range of 2 to 4 wt% at 0.1 wt% Alfoterra and 0.5 wt% SDS. Figure 4.19 shows the increase in the NaCl concentration from 2 to 4 wt% resulting in an increase in the oil removal. This is because the repulsive force between the anionic head groups decreases when the NaCl concentration increases. Consequently, the hydrophobic characteristics of the foam surface increase resulting in increasing amount of oil attached to the foam; hence, the oil removal increases. As shown in Figures 4.20 and 4.21, 4 wt% of NaCl has a relatively high foam ability and foam stability, respectively, as well as a relatively low IFT as illustrates in Figure 4.22. Hence, this is the reason that at 4 wt% NaCl, the system has the highest oil removal.

For effective separation, the overhead froth should have a higher oil concentration than that in the feed. Here, the separation efficiency of the froth flotation is indicated by the enrichment ratio. Figure 4.23 illustrates the effect of NaCl concentration on the enrichment ratio. It shows that an increase in the NaCl concentration from 2 to 4 wt% increases the enrichment ratio of diesel. This is because NaCl reduces the repulsive force between the anionic head groups of the surfactant and so more oil can attach to the foam. Moreover, foam lamella becomes thinner leading to lower water content in the foam and higher oil content. The combined effect between an IFT and a foam production rate (see Figure 4.24) leads to the explanation of the increasing the enrichment ratio of diesel. An increase in the NaCl concentration from 2 to 3 wt%, an IFT result play more significant role than a foam production rate result leads to an increase in the enrichment ratio. The foam production rate decreases when the NaCl concentration further increases from 3 to 4 wt%. This is because further decreasing the repulsive force decreases the thickness of the foam lamella including to the turbulence flow of the solution in the column. Hence, the foam lamella can easily collapse leading to the decreasing of the foam production rate. This relate to an increase of the enrichment ratio. Moreover, the foam wetness was found to have the opposite trend as the enrichment ratio of oil. As seen from Figure 4.25, the foam wetness decreases as the NaCl concentration increases from 2 to 3 wt%. Increasing NaCl concentration produces drier foam. However, the foam production rate can decreases at a very high NaCl concentration of 4 wt%. This is may be due to the slow foam production rate resulting in increasing of water drainage rate in the foam lamella, so the enrichment ratio increases as well as the foam wetness decreases.

The effect of NaCl concentration on surfactant removal is shown in Figure 4.26. An increase in NaCl concentration from 2 to 3 wt% results in increasing surfactant removal because of the reduction of the repulsive force between the anionic head groups. Therefore, more surfactants can adsorb at the air-solution interface and then, the removal of surfactant increases. The surfactant removal decreases when the NaCl concentration is increased from 3 to 4 wt%. This can be explained by the effect of salinity on the foam production flow rate as described previously.

Figure 4.27 shows that the enrichment ratio of surfactant increases with increasing NaCl concentration from 2 to 3 wt%. When the NaCl conentration is further increased from 3 to 4 wt%, the enrichment ratio of surfactant decreases. Again, this can be explained by the same reason for the effect of foam production rate.

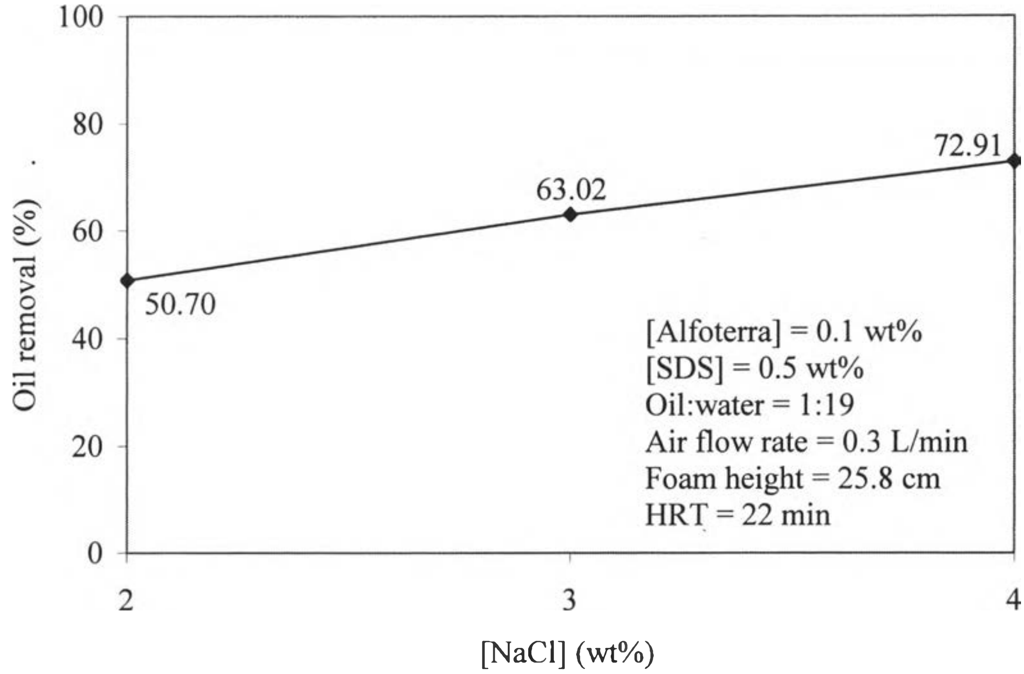

Figure 4.19 Removal efficiency of diesel at different feed NaCl concentrations.

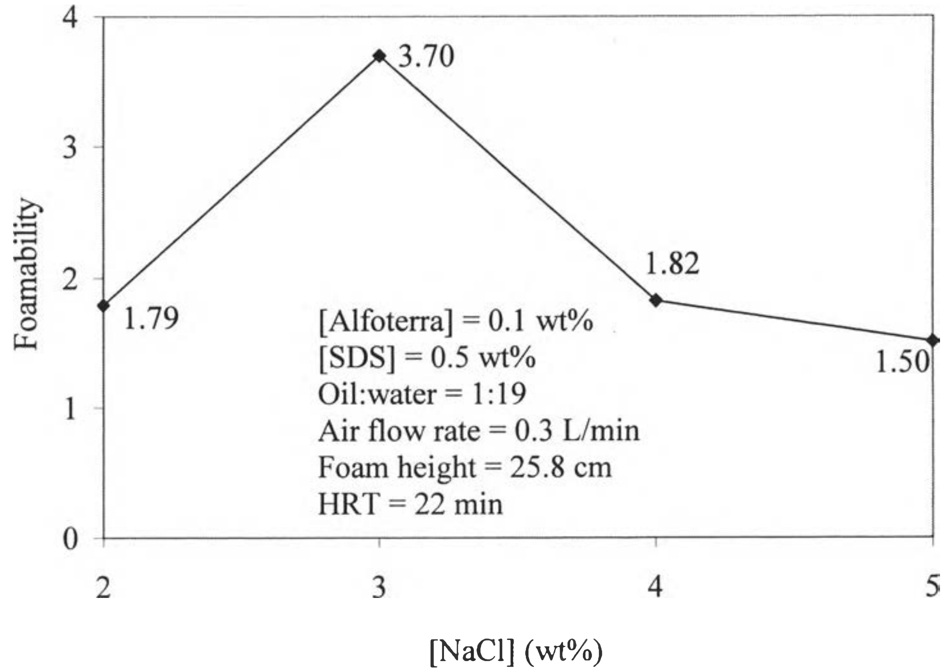

Figure 4.20 Foamability at different NaCl concentrations.

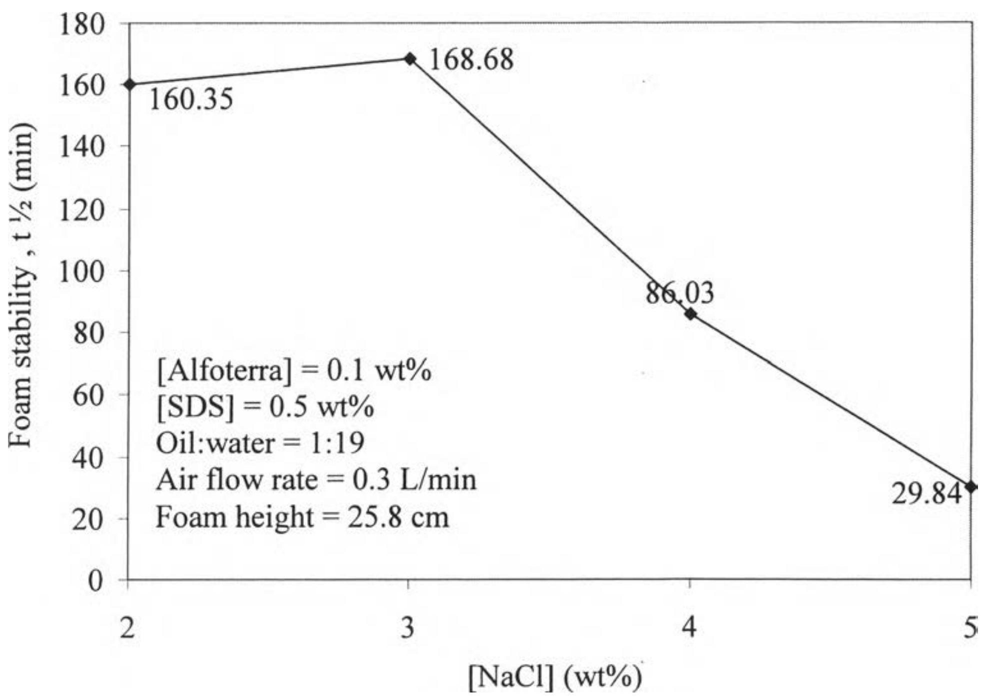

Figure 4.21 Foam stability with different NaCl concentrations.

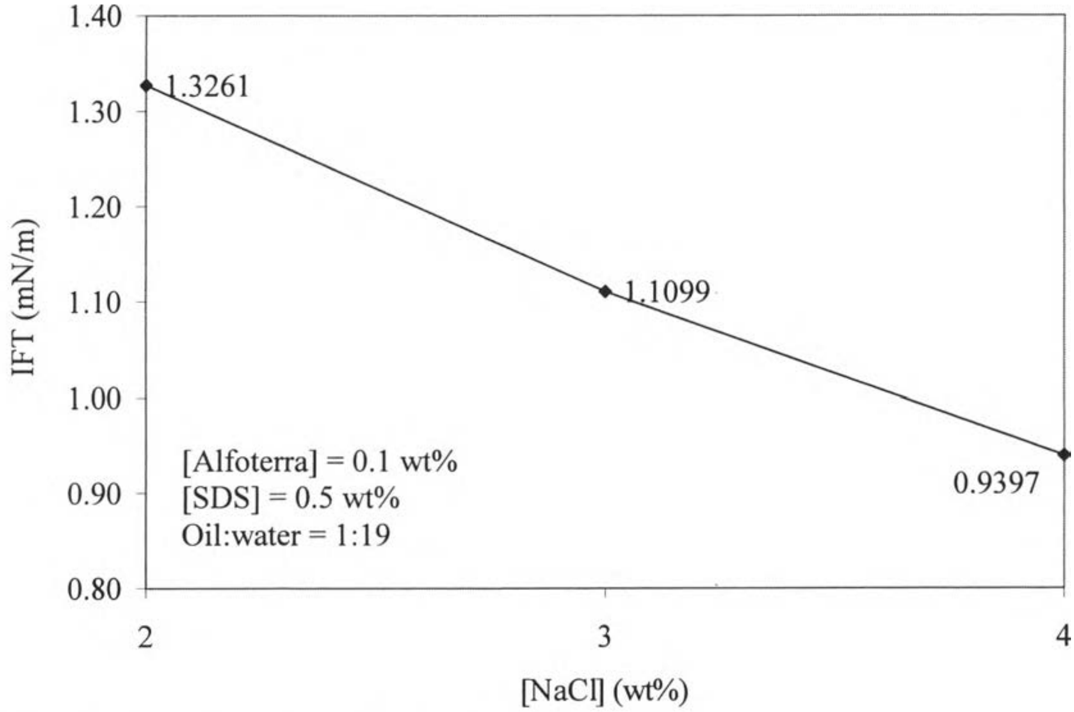

Figure 4.22 IFT with different NaCl concentrations.

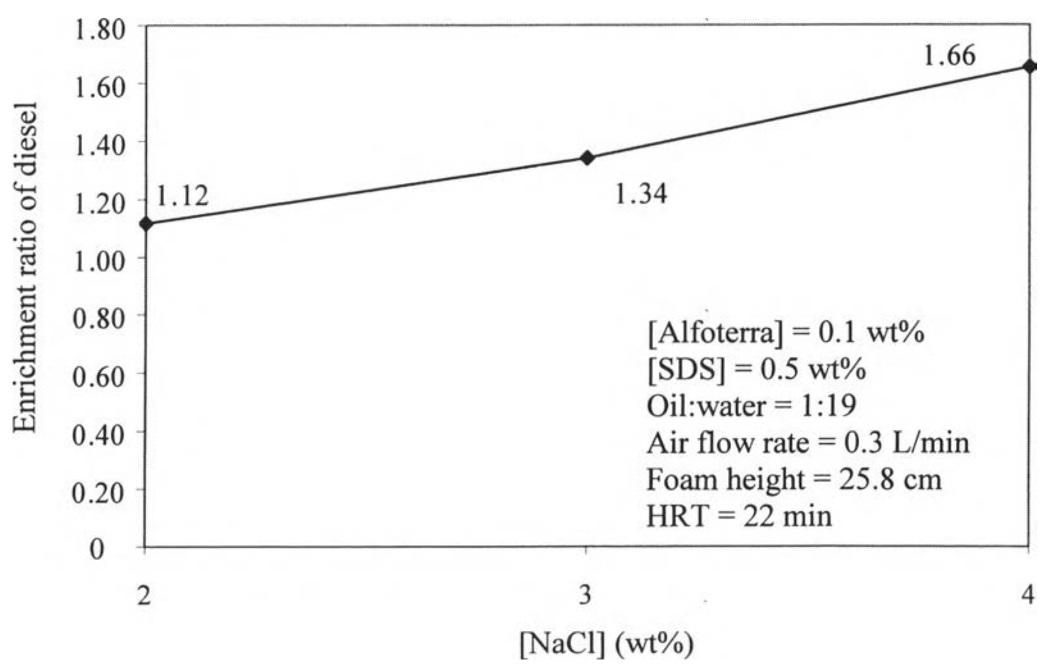

Figure 4.23 Enrichment ratio of diesel with different NaCl concentrations.

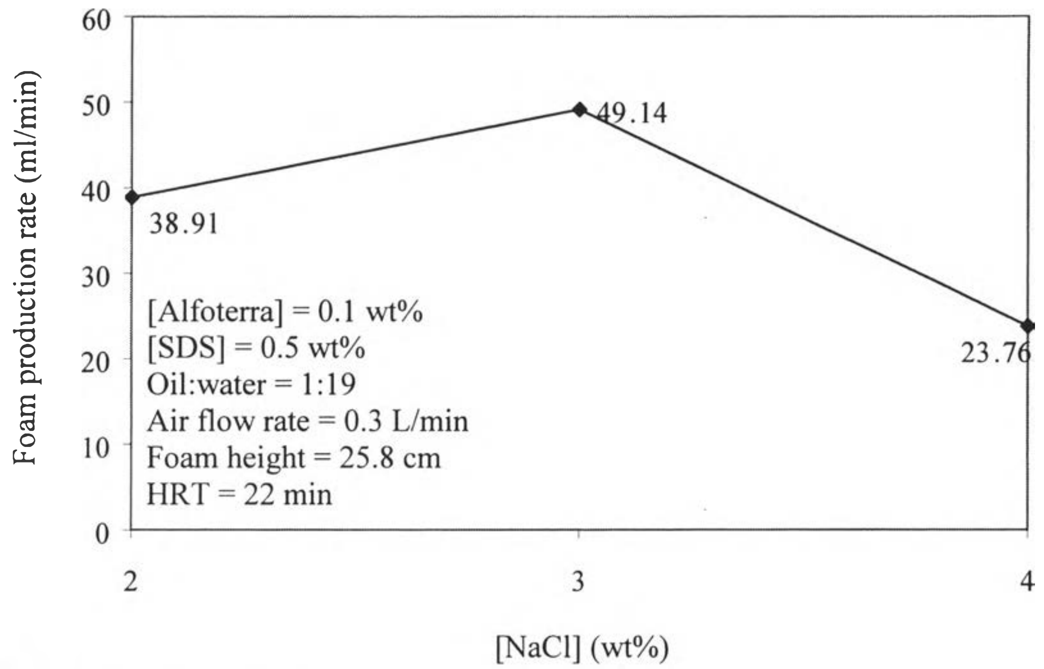

Figure 4.24 Foam production rate with different NaCl concentrations.

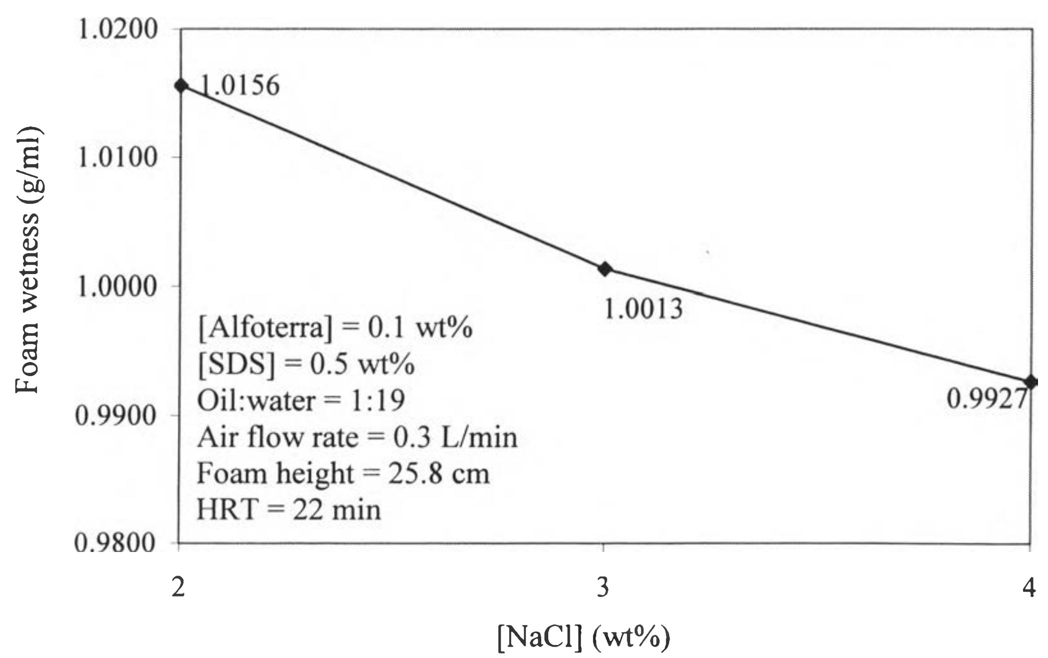

Figure 4.25 Foam wetness with at different NaCl concentrations.

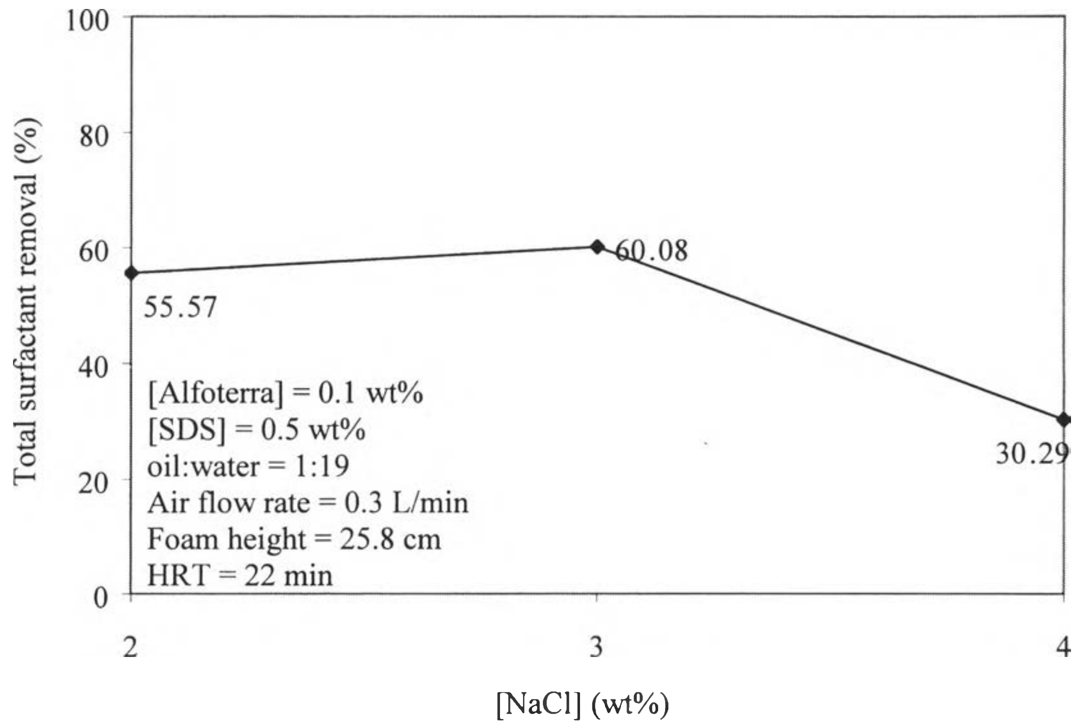

Figure 4.26 Surfactant removal with at different NaCl concentrations.

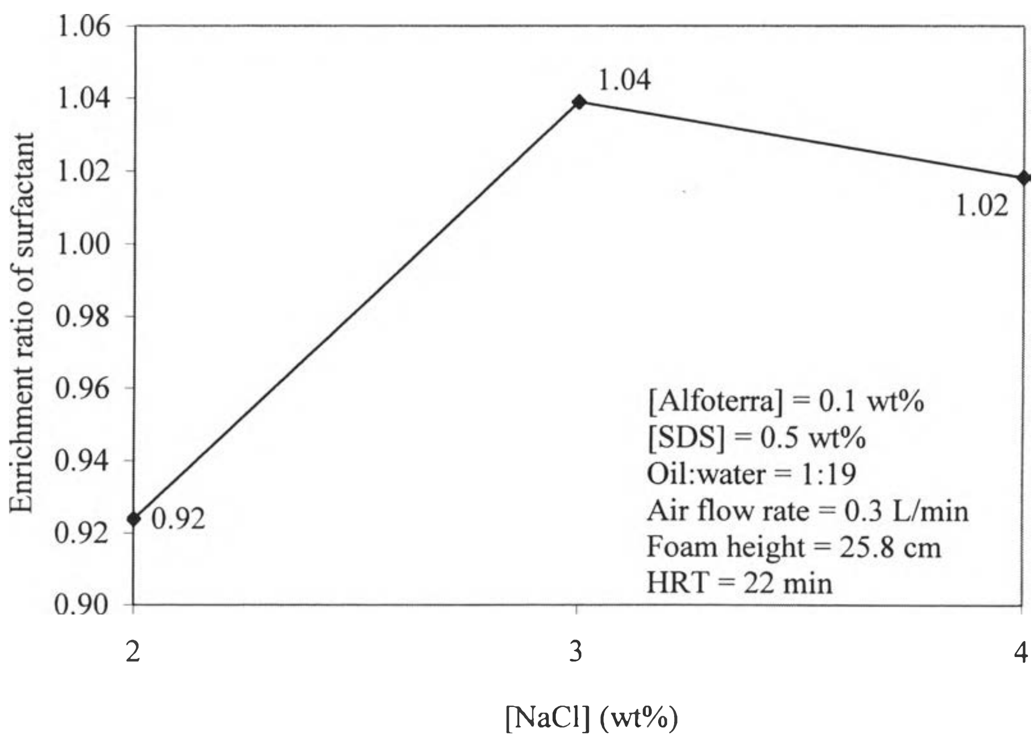

Figure 4.27 Enrichment ratio of surfactant with different NaCl concentrations.

4.2.4 Effect of Oil to Water Ratio on the Performance of Froth Flotation

Most available work on froth flotation involves 1:1 oil to water ratio (Chavadej *et al.*, 2003, Feng *et al.*, 2000). Practically, in the real situation, a ratio of emulsified oil to wastewater is much less than 1:1. Consequently, in this work, the effect of oil loading on the performance of froth flotation was investigated by varying the oil to water ratio, 1:199, 1:99, 1:19, and 1:9 at 0.1 wt% of Alfoterra, 0.5 wt% of SDS, and 4 wt% of NaCl. As illustrated in Figure 4.28, the effect of oil to water ratio on diesel removal corresponds to the result of foam ability and foam production rate as shown in Figure 4.29 and Figure 4.30. This is because at high foam production rate, the drainage rate of water in the foam lamella decreases resulting in decreasing back-entrainment of oil content into the solution in the column leading to the high oil removal. In the other hands, at low foamability and foam production rate, so the water drainage rate increases leading to the high content of diesel back-entrainment into the column, so the oil removal declines. It was found that oil to water ratio is not affected significantly on oil removal efficiency.

Figure 4.32 shows the effect of oil to water ratio on the enrichment ratio of diesel. The enrichment ratio decreases slightly when the oil to water ratio increases from 1:199 to 1:99. This is because at an oil to water ratio of 1:99, both foamability and foam production rate are increased resulting in having wetter foam as compared to an oil to water ratio of 1:199. As a result, the collapsed foam contains a high amount of water leading to a lower enrichment ratio of diesel. After that, when an oil to water ratio further is increased to 1:19, the enrichment ratio of oil increases substantially. This is because at an oil to water ratio of 1:19, the system has the very low foamability and foam stability (see Figure 4.30) as well as a low foam production rate (see Figure 4.31) leading to a lowering content of water. Therefore, the enrichment ratio of diesel increases. When an oil to water ratio is further increased to 1:9, the enrichment ratio of diesel relating decreases again. The explanation is still the same as described before. As expected, the profile of foam wetness (see Figure 4.33) is the opposite trend of the enrichment ratio of diesel. The higher foam wetness, the higher water content is or the lower oil content is.

As shown in Figure 4.34, the trend of surfactant removal as a function of oil to water ratio corresponds to those of foamability and foam production rate of system. A lower foam production rate indicates more water back-entrainment resulting in a higher amount of surfactant entrained back into the solution in the column. As a result, surfactant removal decreases. In the contrast, when foam production rate is higher, a less amount of water back-entrainment into the solution in the column, hence the removal of surfactant is high.

Figure 4.35 shows the effect of oil to water ratio on enrichment ratio of surfactant. The enrichment ratio of surfactant also relates to the foamability and the foam production rate as shown in Figures 4.29 and 4.31, respectively. At a higher foam production rate, a lower quantity of water is entrained back into the solution in the column, hence the amount of water in the collapsed froth become higher leading to a lower enrichment ratio of surfactant. In the contrast, when foam production rate is low leading to the high water back-entrainment into the solution in the column, hence low amount of water contained in the foam lamella resulting in the high enrichment ratio of surfactant.

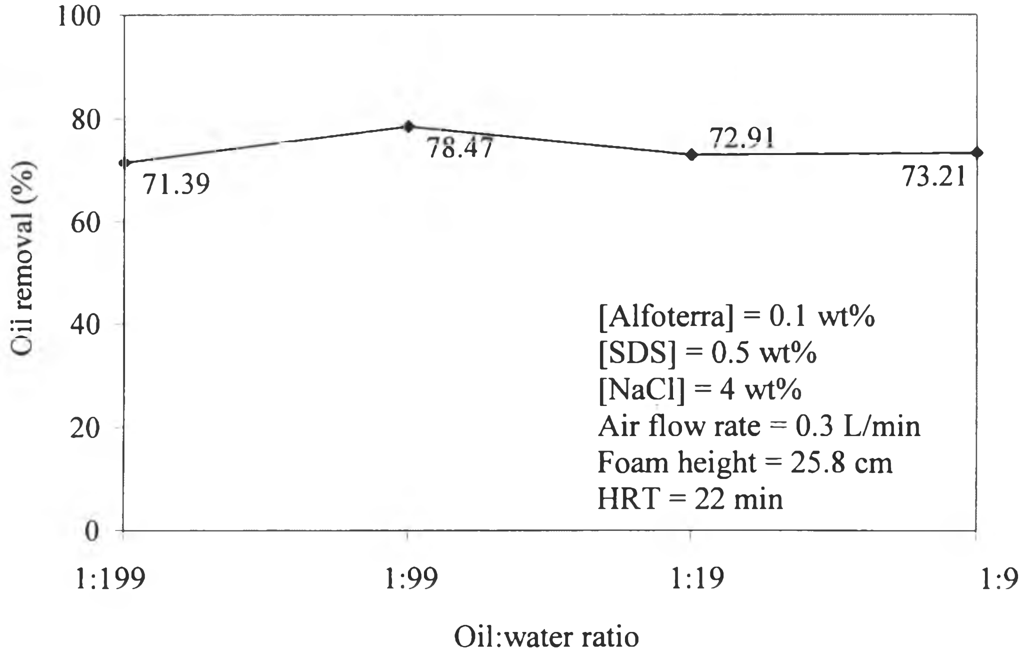

Figure 4.28 Removal efficiency of diesel of system at different feed oil to water ratios.

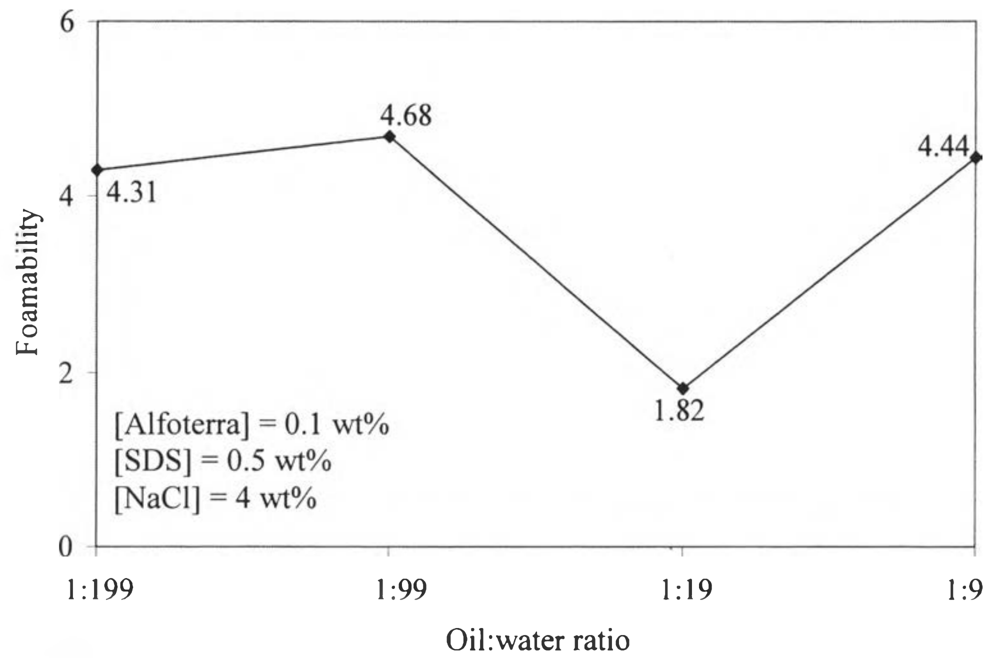

Figure 4.29 Foamability of system at different feed oil to water ratios.

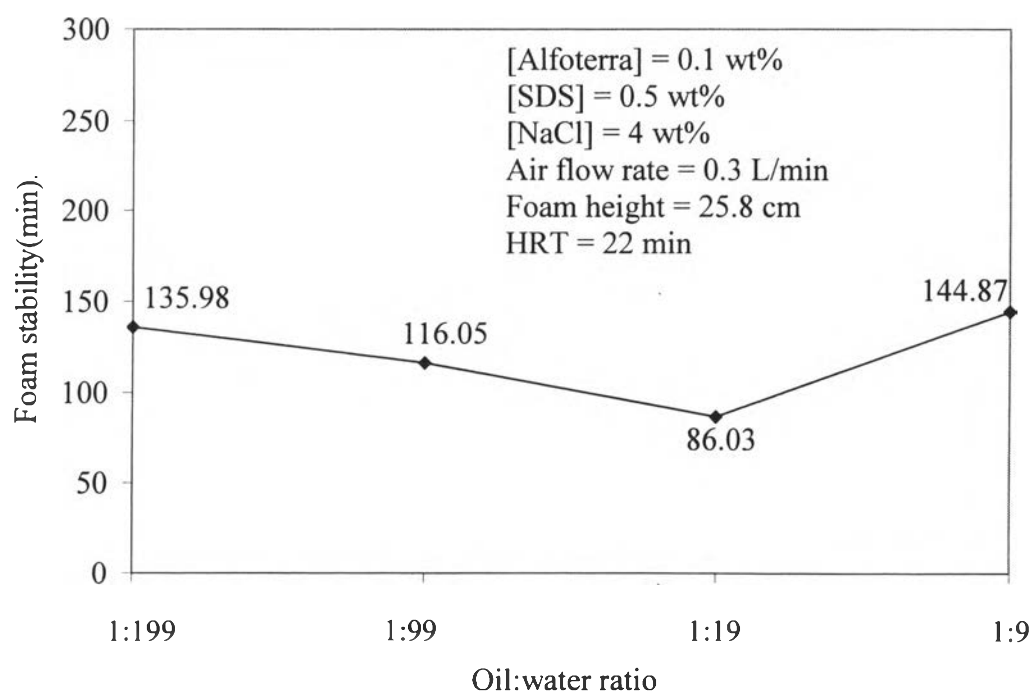

Figure 4.30 Foam stability of system at different initial oil to water ratios.

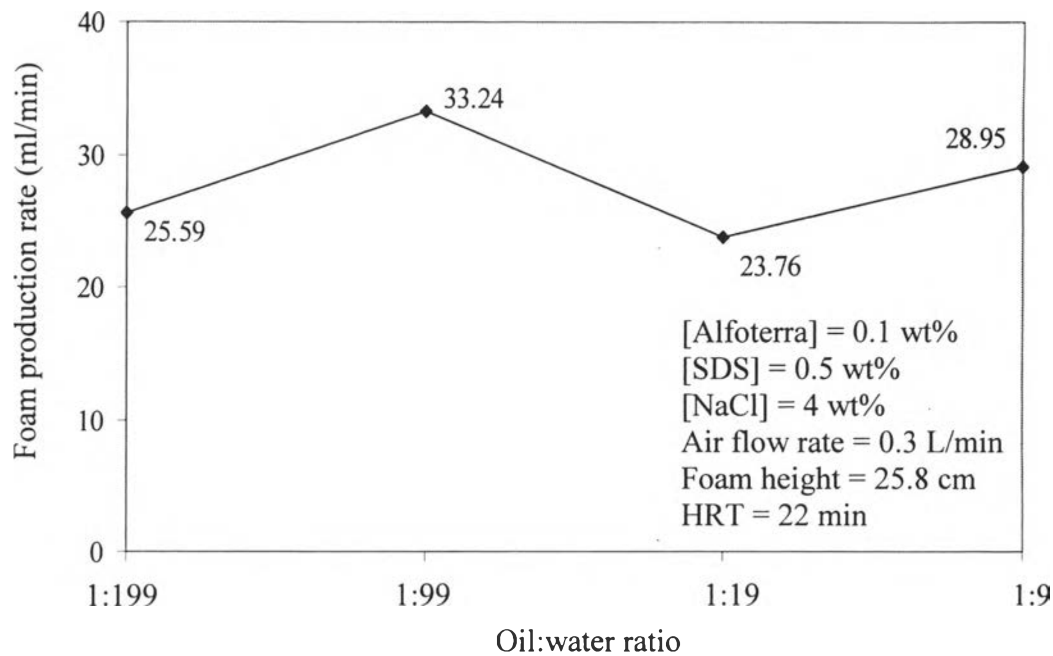

Figure 4.31 Foam production rate of system at different feed oil to water ratios.

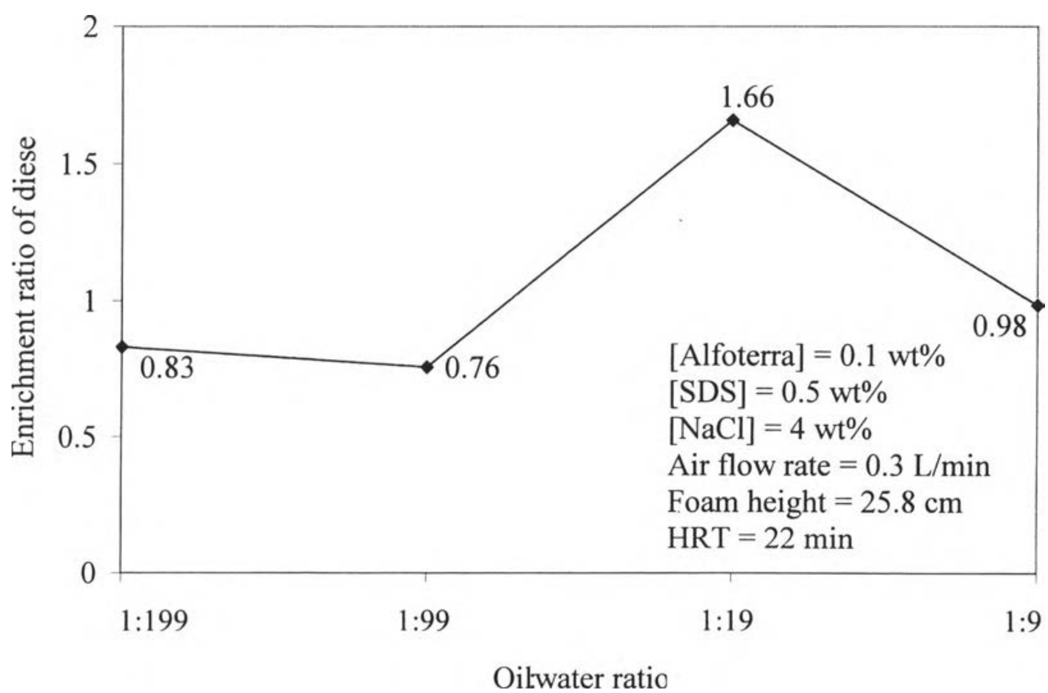

Figure 4.32 Enrichment ratio of diesel of system at different feed oil to water ratios.

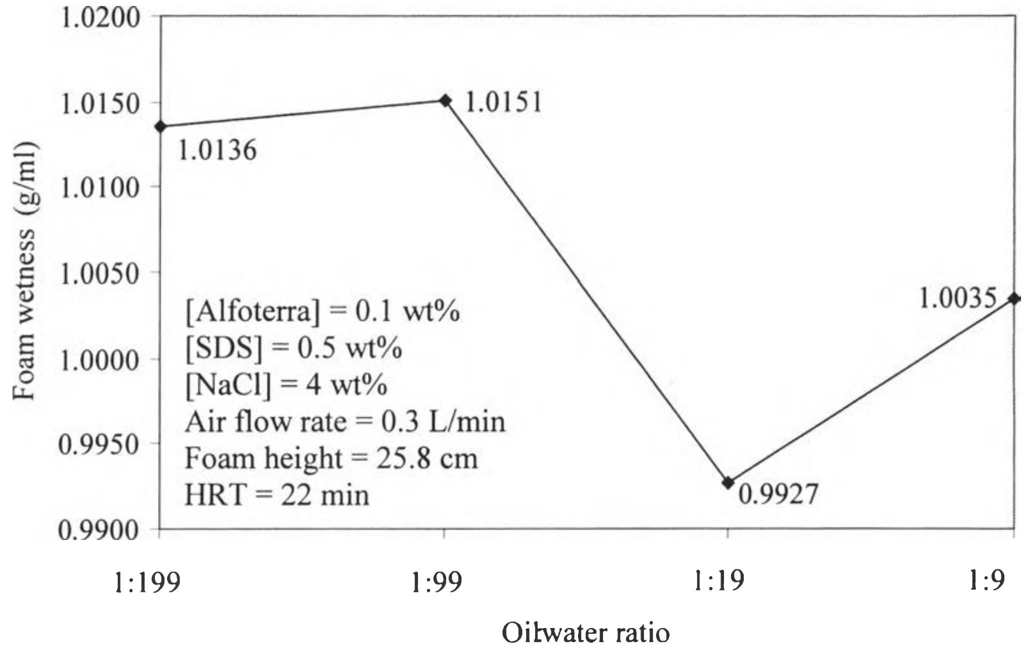

Figure 4.33 Foam wetness of system at different feed oil to water ratios.

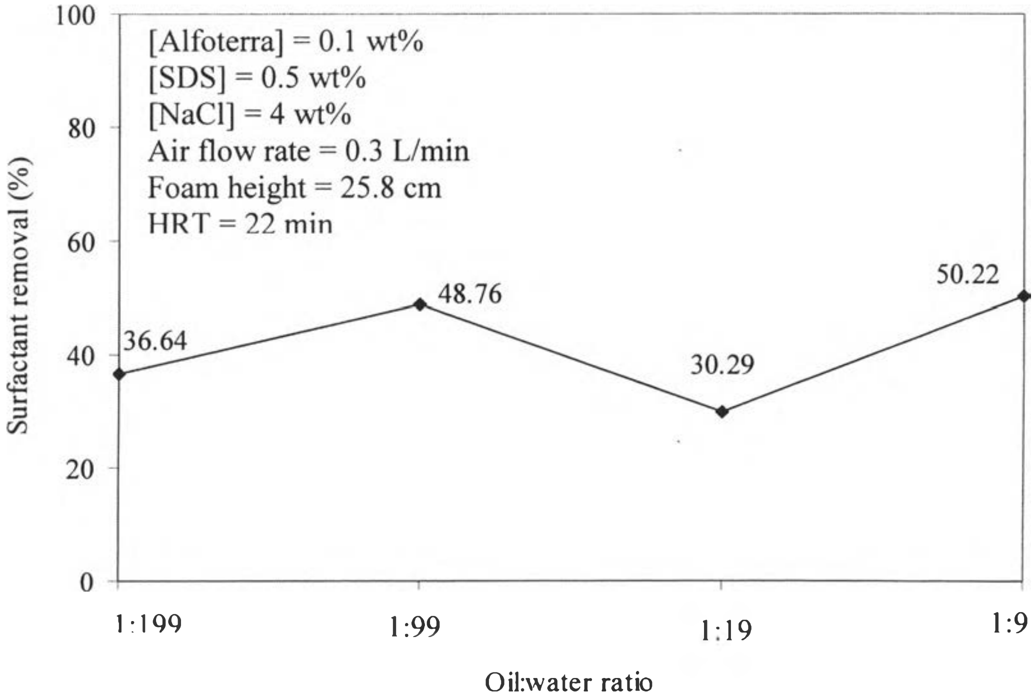

Figure 4.34 Surfactant removal of system at different feed oil to water ratios.

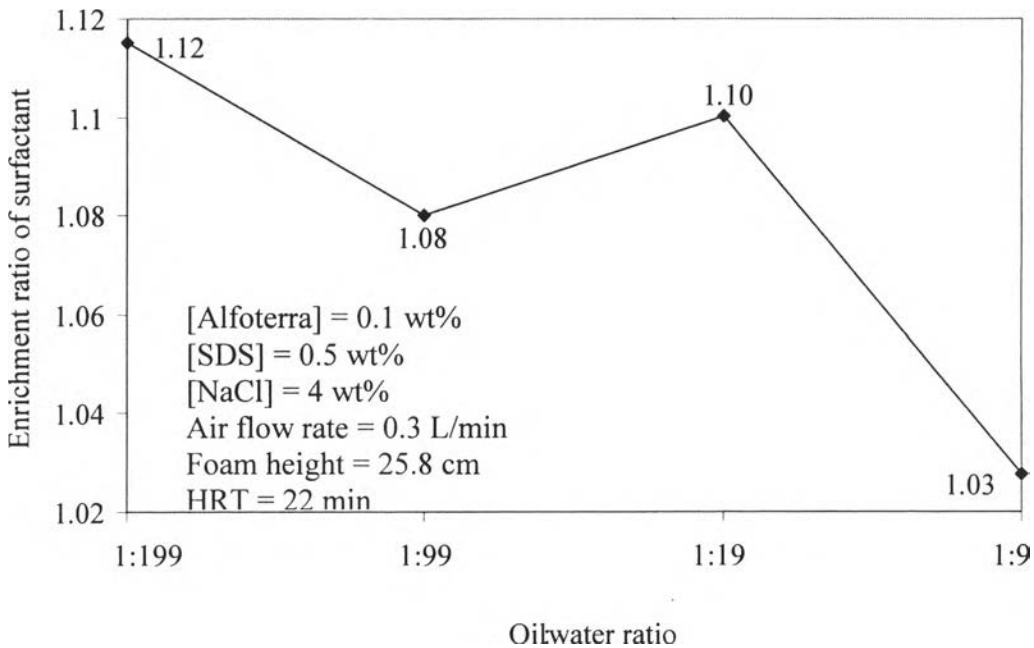

Figure 4.35 Enrichment ratio of surfactant of system at different feed oil to water ratios.

4.2.5 Effect of Air Flow Rate on Performance of Froth Flotation

Air flow rate is one of the vital parameters in forth flotation operation. A mixture of 0.1 wt% of Alfoterra, and 0.5 wt% of SDS, at 4 wt% of NaCl was selected to run froth flotation since the system could offer the highest oil removal.

As can be seen in Figure 4.36, oil removal efficiency is not affected significantly by the increasing air flow rate in range of 0.15 to 0.25 L/min. while the foamability of the system, foam wetness and foam production rate increase almost linearly as shown in Figures 4.37, 4.38 and 4.39, respectively. However at an air flow rate higher than 0.30 L/min, the oil removal decreases slightly with increasing air flow rate. With increasing air flow rate from 0.25 to 0.3 L/min, the foamability, the foam wetness and the foam production rate increase slightly while the foam stability decreases. From Figure 4.40, increasing air flow rate affects insignificantly the foam stability of the system in the range from 0.15 to 0.25 L/min.

However, the foam stability of system decreases significantly with increasing air flow rate from 0.25 to 0.3 L/min.

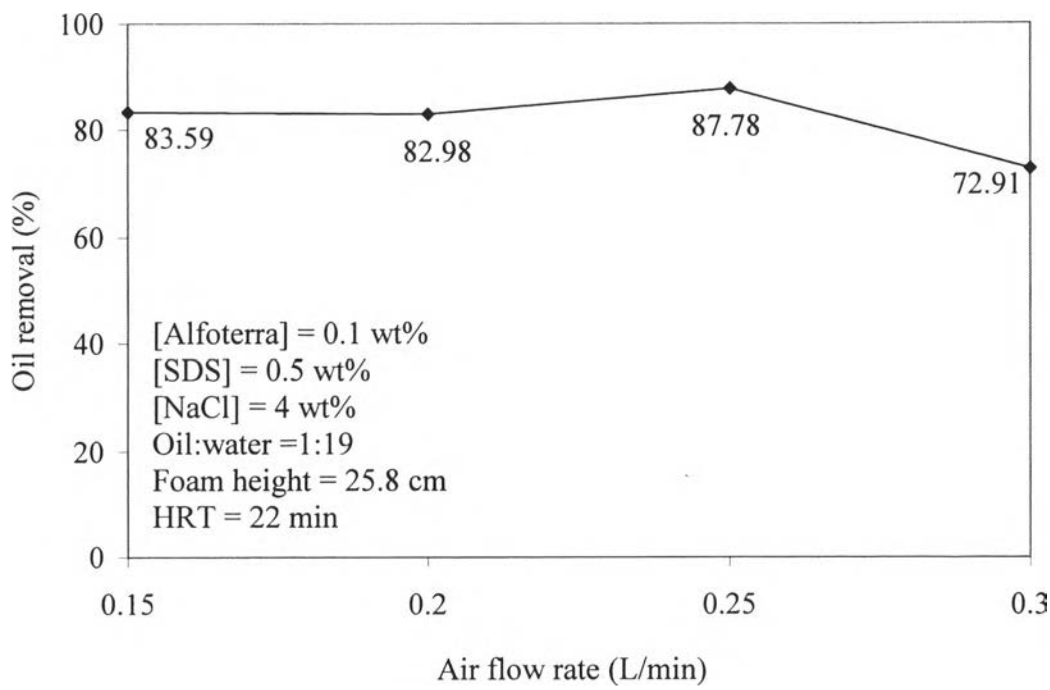

Figure 4.36 Oil removal of system at different air flow rates.

As a result, the oil removal at air flow rate 0.3 L/min decreases. This is because increasing air flow rate leads to have more bubble swarm passing through the solution. Not only a number of bubbles in the solution but also the flow pattern in the solution that are affected by a high air flow rate. The circulation velocity induced by the bubble swarm rising through the column enhances the turbulence at the froth/collection zone interface, so some diesel adsorbed in the froth is entrained back into the solution at this high air flow rate of 0.3 L/min.

Figure 4.39 shows the effect of air flow rate on enrichment ratio of diesel. The higher air flow rate, the lower the enrichment ratio of diesel is obtained. This can be explained that a higher air flow rate simply produces more bubbles passing through the solution resulting in a higher foam production rate, with wetter foam as shown in Figure 4.38. As a result the enrichment ratio of diesel decreases.

Figure 4.42 shows the effect of air flow rate on the surfactant removal. Increasing the air flow rate from 0.15 to 0.25 L/min results in insignificant effect on the surfactant removal but at an air flow rate of 0.30 L/min, the surfactant removal decreases. This can be explained by using the combined effects of the foamability, the foam stability and the enrichment ratio of surfactant.

The enrichment ratio of surfactant decreases as the air flow rate increases as illustrated in Figure 4.43. This corresponds to the result of the foam flow rate. A high air flow rate results in a high foam flow rate leading to more difficulty for water drainage from the foam lamella and so there is a high amount of water in the collapsed foam as well as a low enrichment ratio of surfactant.

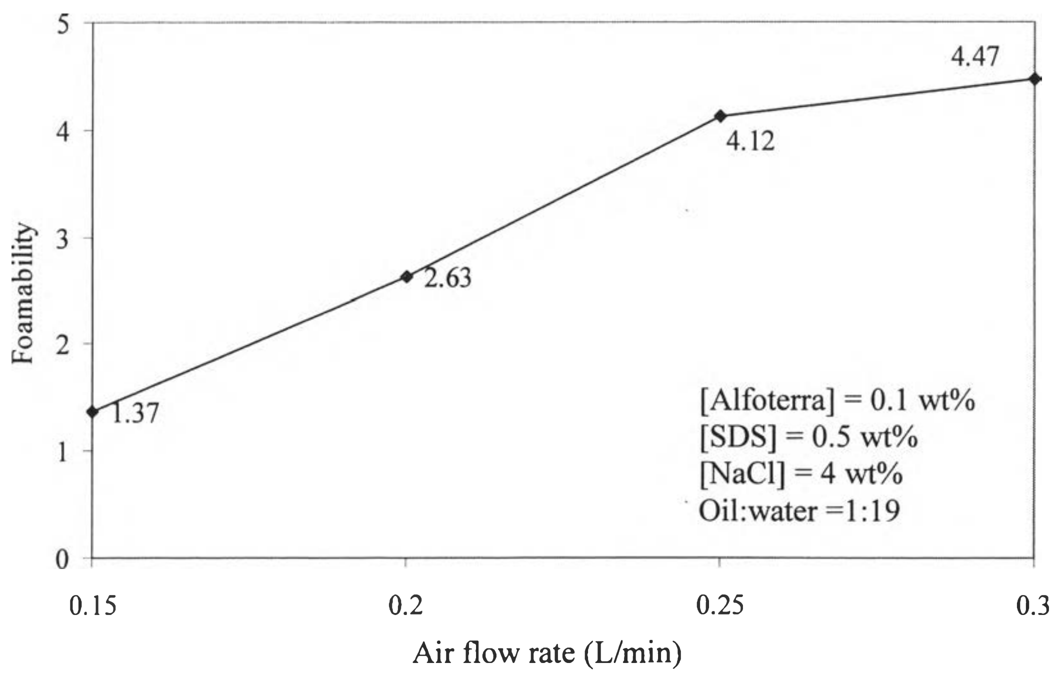

Figure 4.37 Foamability of diesel of system at different air flow rates.

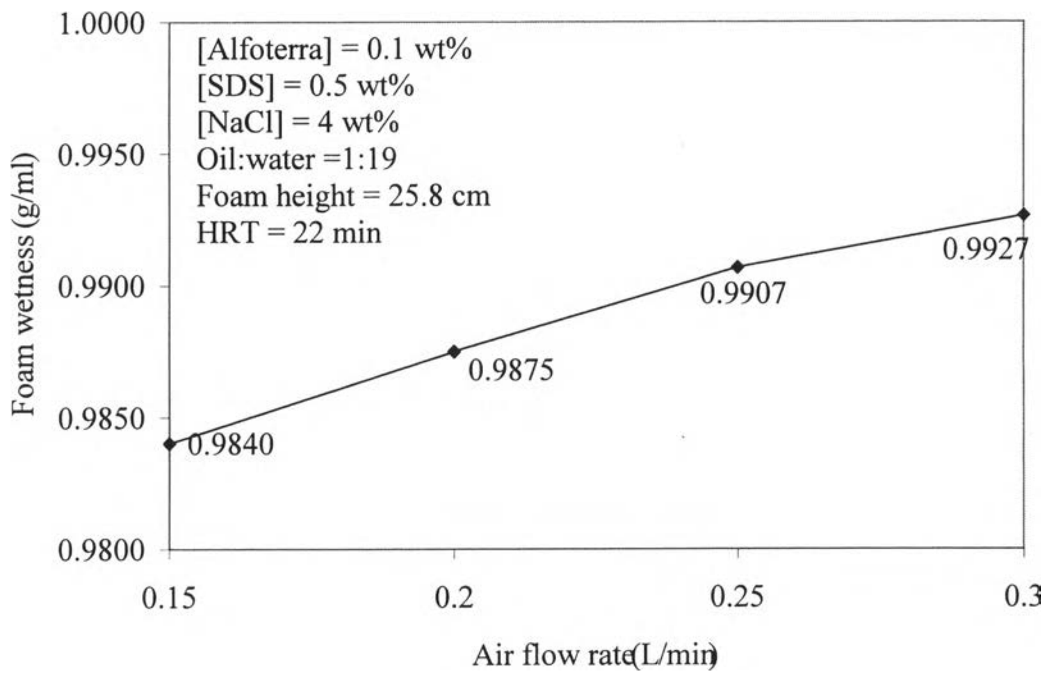

Figure 4.38 Foam wetness of system at different air flow rates.

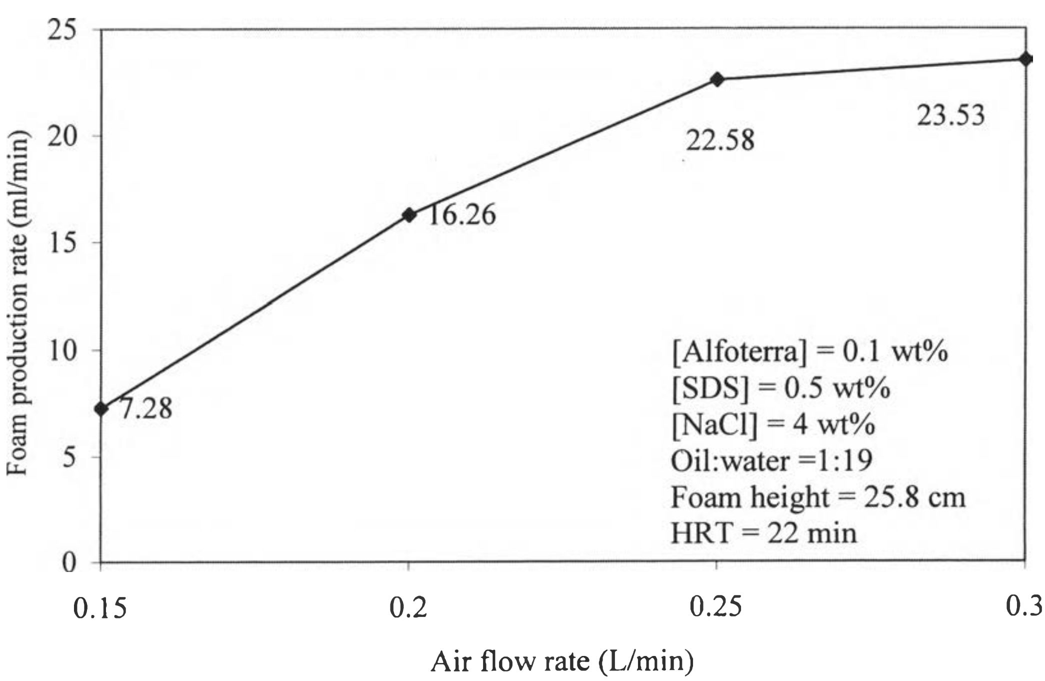

Figure 4.39 Foam production rate of system at different air flow rates.

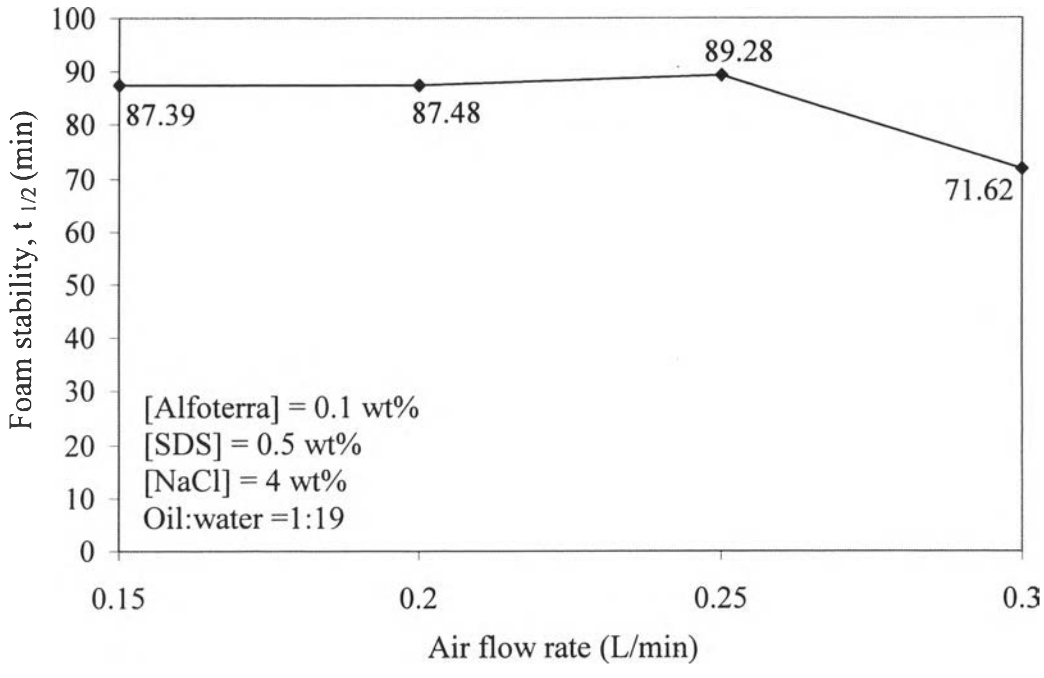

Figure 4.40 Foam stability of diesel of system at different air flow rates.

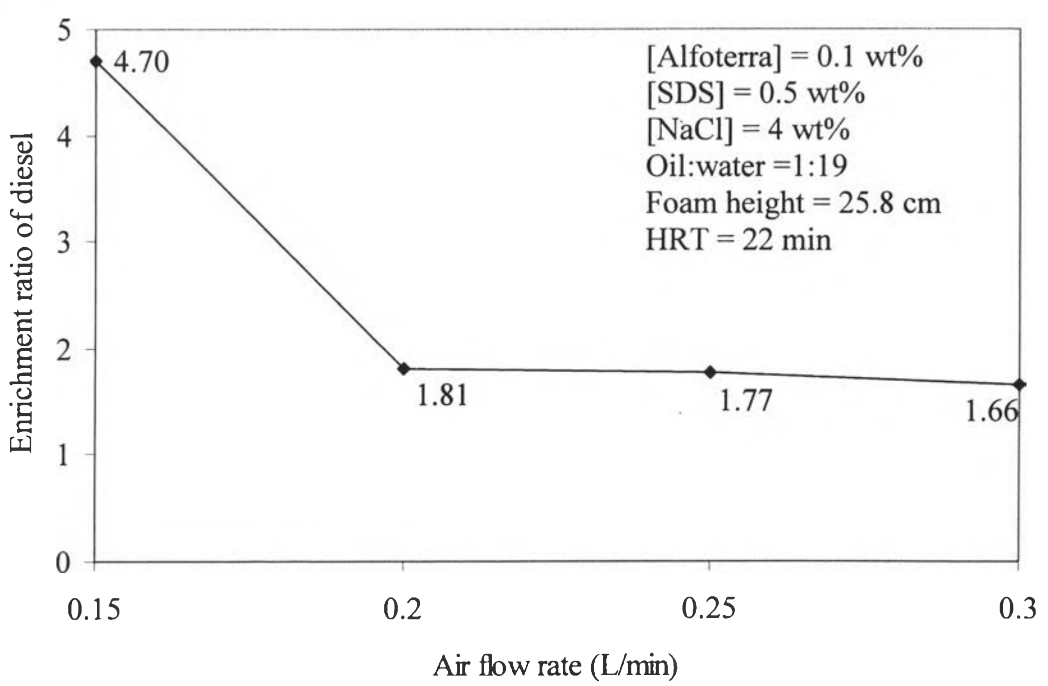

Figure 4.41 Enrichment ratio of diesel of system at different air flow rates.

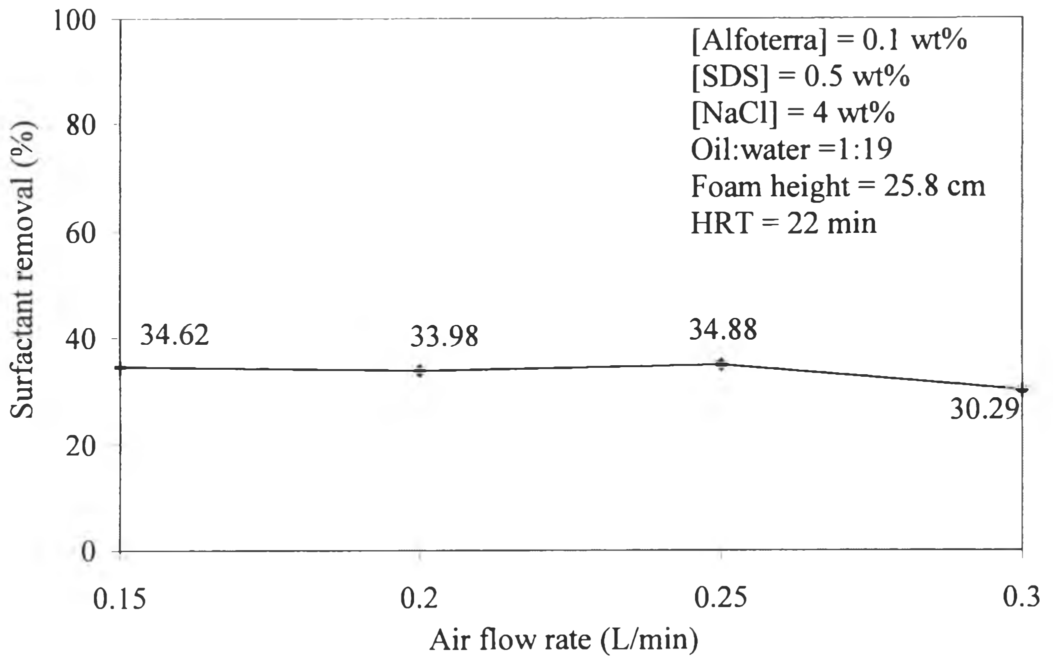

Figure 4.42 Surfactant removal of system at different air flow rates.

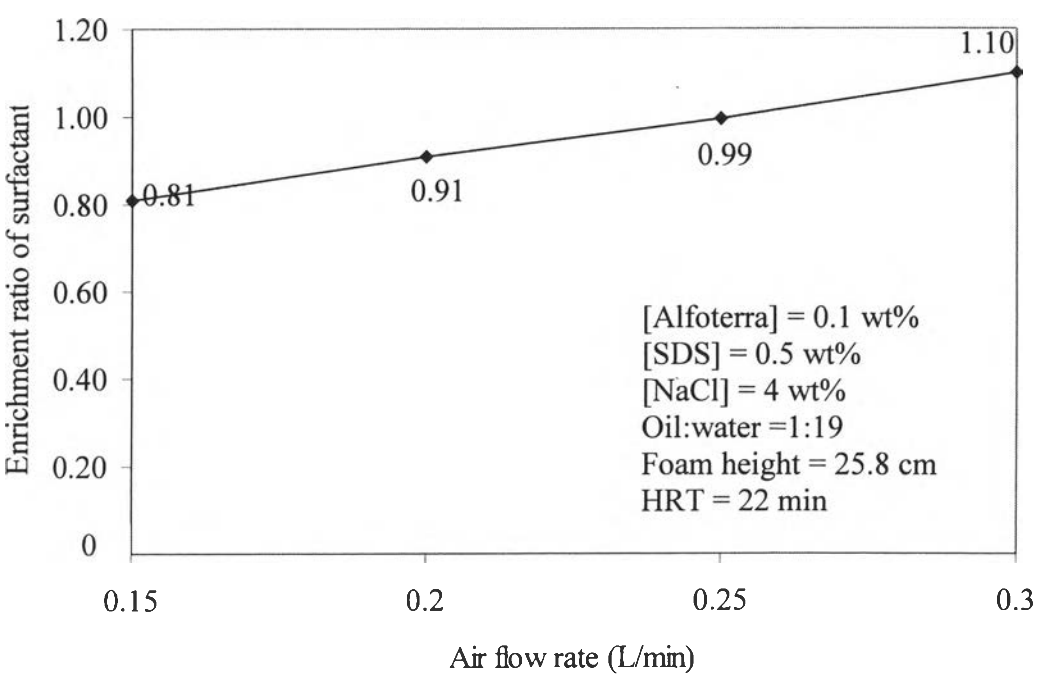

Figure 4.43 Enrichment ratio of surfactant of system at different air flow rates.

4.2.6 Effect of Hydraulic Retention Time (HRT) on Performance of Froth Flotation

From Figure 4.44, oil removal increases when HRT increases. This is because at a higher HRT represents a longer residence time for the solution to be contact with air bubbles. As a result, a higher amount of oil can be carried on to the top of the column and a higher oil removal is obtained.

As shown in Figure 4.45, the enrichment ratio of oil increases as HRT increases because a high HRT represents a lower feed flow rate resulting in more time of oil stay in the column as well as more time to be contacted and attached to the air bubbles and the froth at the top of the column. Therefore, in the collapsed froth contains a higher amount of oil and smaller water content with increasing HRT. As expected, increasing HRT resulting in decreasing foam wetness (see Figure 4.46). This corresponds to the result of the enrichment ratio of oil because at a higher HRT, the system simply has a long time for allowing more water drainage for the foam produced. As a result, the foam wetness and the foam production rate decrease as shown in Figures 4.46 and 4.47, respectively.

Figure 4.48 and Figure 4.49 show the effects of HRT on surfactant removal and enrichment ratio of surfactant, respectively. With increasing HRT in the range 9.9 to 20 min, the effects of HRT on both surfactant removal and enrichment ratio of surfactant is insignificant but at the highest HRT, both removal and enrichment ratio of surfactant increase remarkably. The results indicate that at a low HRT, a proper balance between the foam production rate and the rate of water drainage from the foam attributes to relatively constant values of both removal and enrichment ratio of surfactant. However, at a very high HRT of 49 min, the rate of water drainage becomes prominent resulting in both higher values of the removal and enrichment ratio of surfactant.

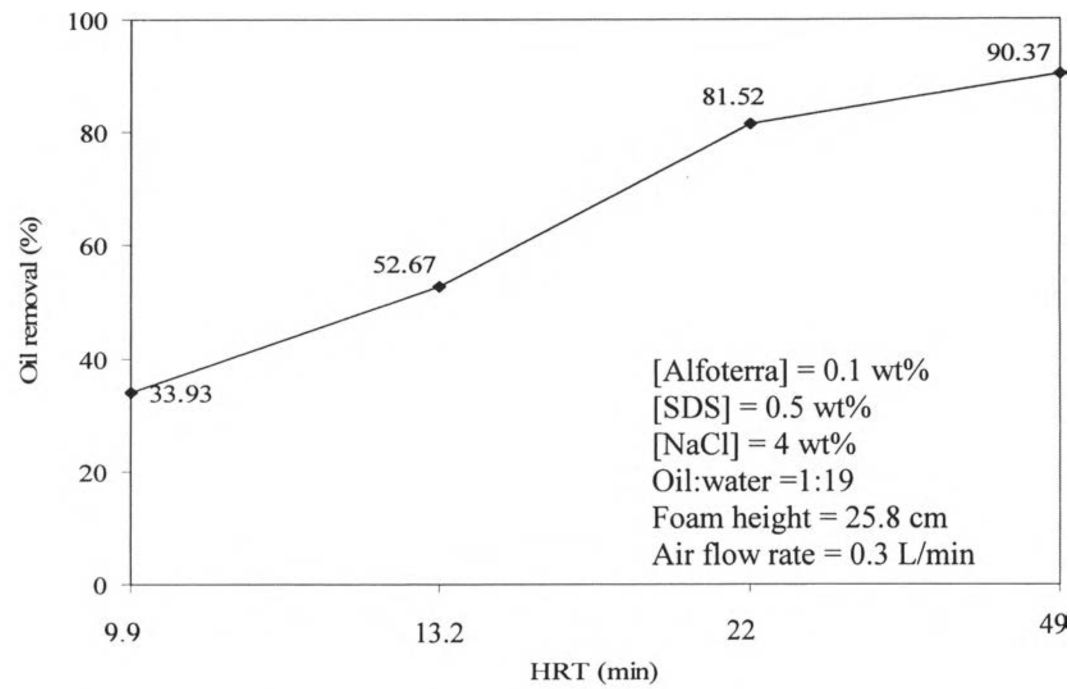

Figure 4.44 Oil removal of system at different HRTs.

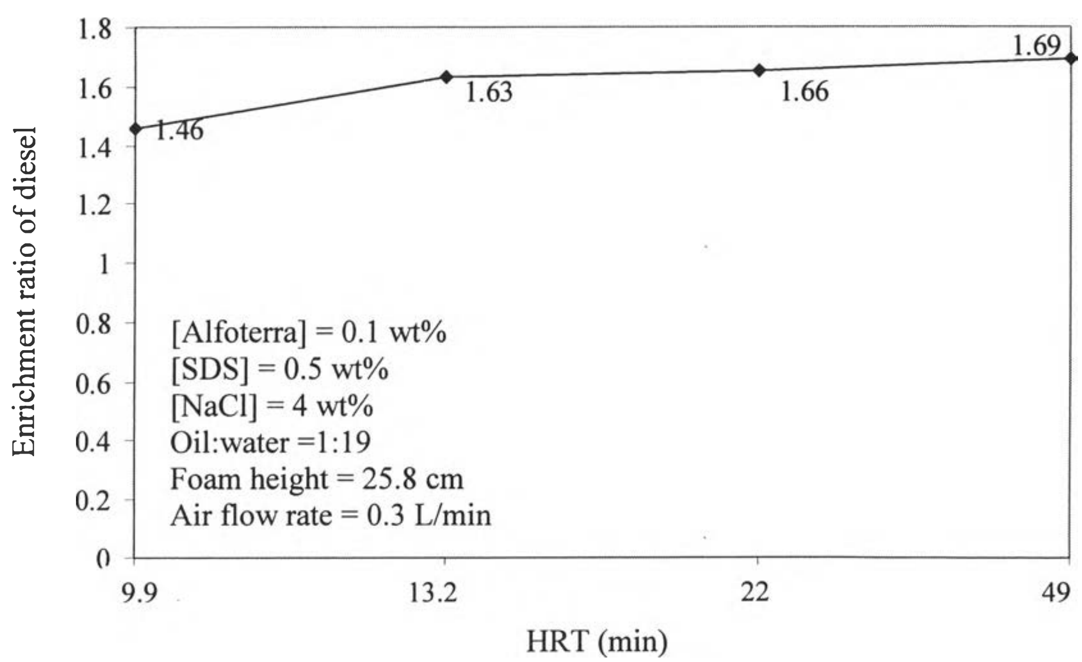

Figure 4.45 Enrichment ratio of diesel at different HRTs.

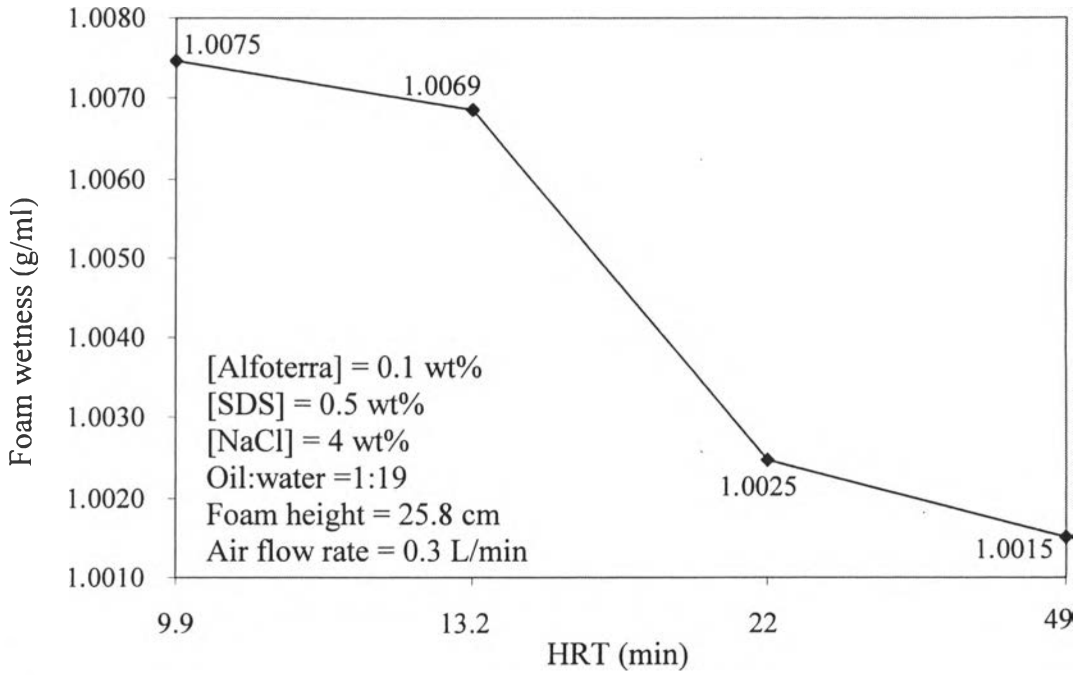

Figure 4.46 Foam wetness of system at different HRTs.

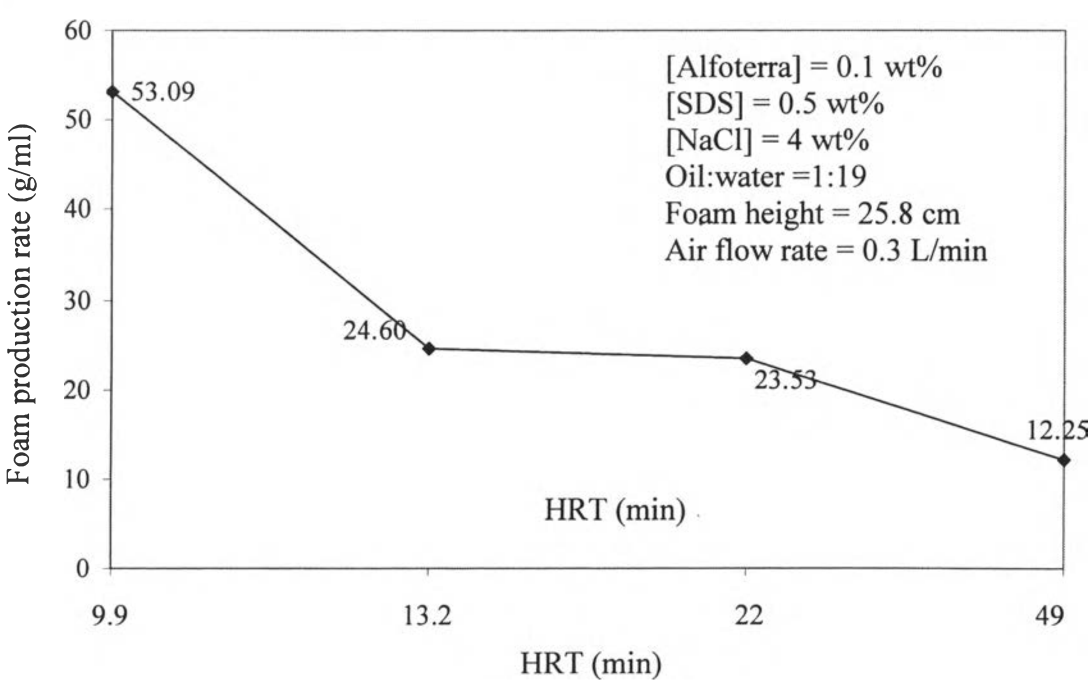

Figure 4.47 Foam production rate of system at different HRTs.

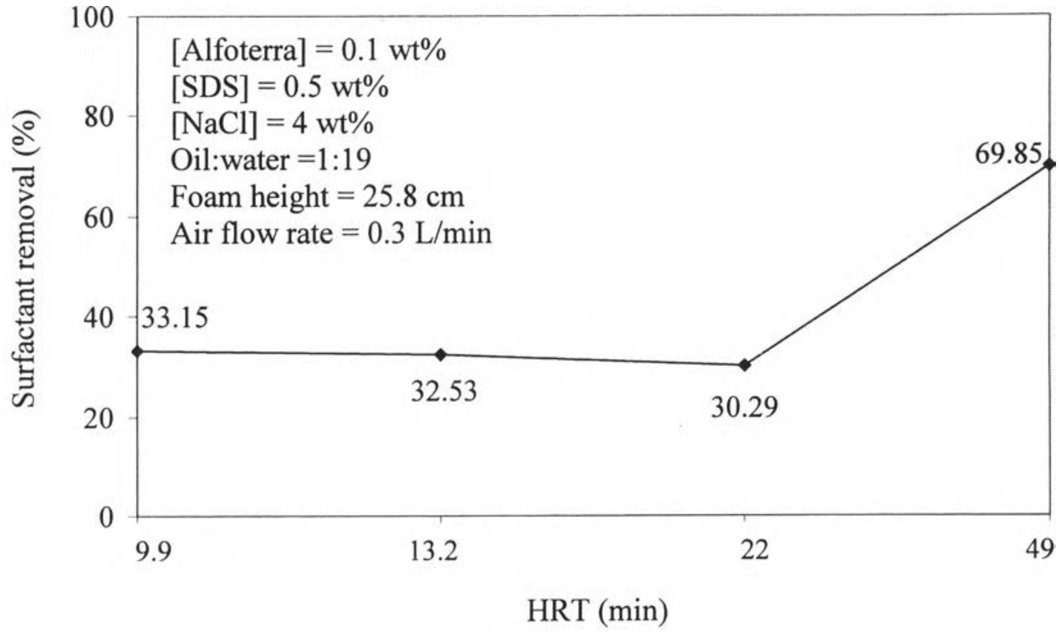

Figure 4.48 Surfactant removal of system at different HRTs.

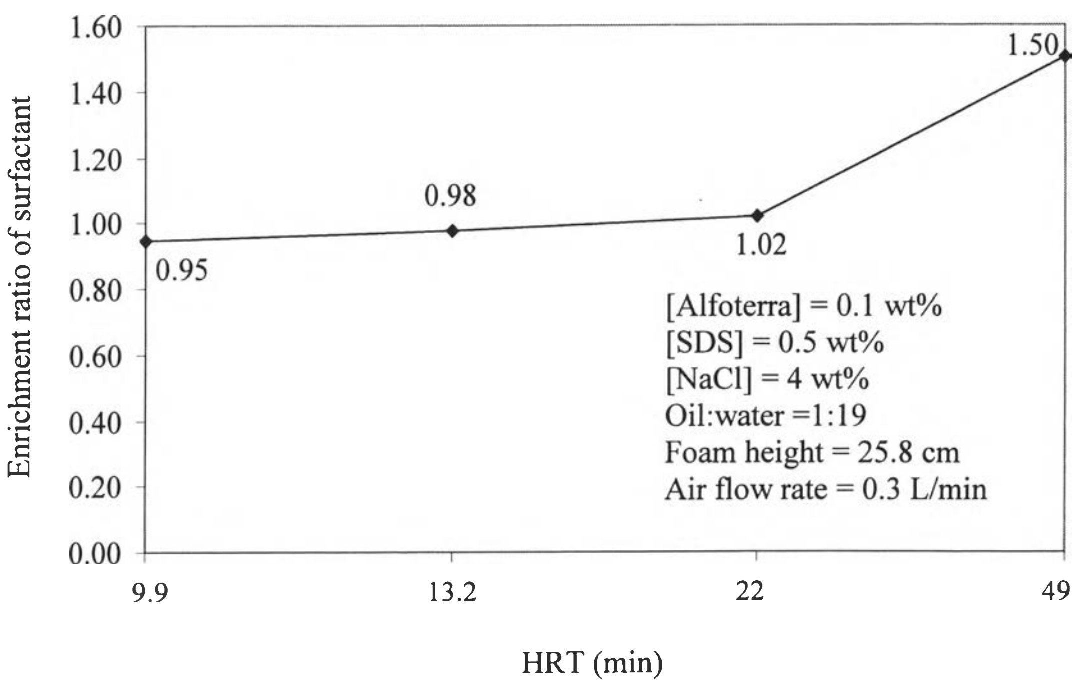

Figure 4.49 Enrichment ratio of surfactant of system at different HRTs.

4.2.7 Effect of Foam Height on the Performance of Froth Flotation

Foam height is also a parameter affecting the performance of froth flotation operation. Figure 4.50 shows an increase in foam height resulting in decreasesing oil removal efficiency. When a foam height increases, a foam production rate decreases as shown in Figure 4.51. This is because the foam produced tends to collapse more easily and so the possibility that more oil is entrained back into the solution causing a lower oil removal efficiency.

Moreover, a contrast trend of enrichment ratio of oil was found. As can be seen from Figure 4.52, the enrichment ratio of oil increases as the foam height increases because when the foam height increases leading to lower foam production rate as shown in Figure 4.51 resulting in a higher rate of the water back entrainment. Hence, the foam produced contains a lower amount of water or a higher enrichment ratio of oil. This can be supported by the foam wetness result because a high enrichment ratio of oil relates to a lower content of water in the foam, so foam wetness decreases as foam height level increases (see Figure 4.53).

As can be seen from Figure 4.54, the surfactant removal decreases as the foam height increases. This is because at high foam height leading to a low foam production rate as shown in Figure 4.53. As a result from having a high water back-entrainment into the solution in the column, there is a high possibility that surfactant is entrained back into the solution in the column. Hence, the surfactanrt removal efficiency decreases with increasing foam height.

Moreover, the enrichment ratio of surfactant increases when the foam height increases as illustrated in Figure 4.55. This is because when foam height increases leading to a low foam production rate as shown in Figure 4.53. Consequently, the rate of water back entrainment increases and, so foam contains a lower amount of water or high enrichment ratio of surfactant in the collapsed froth is obtained.

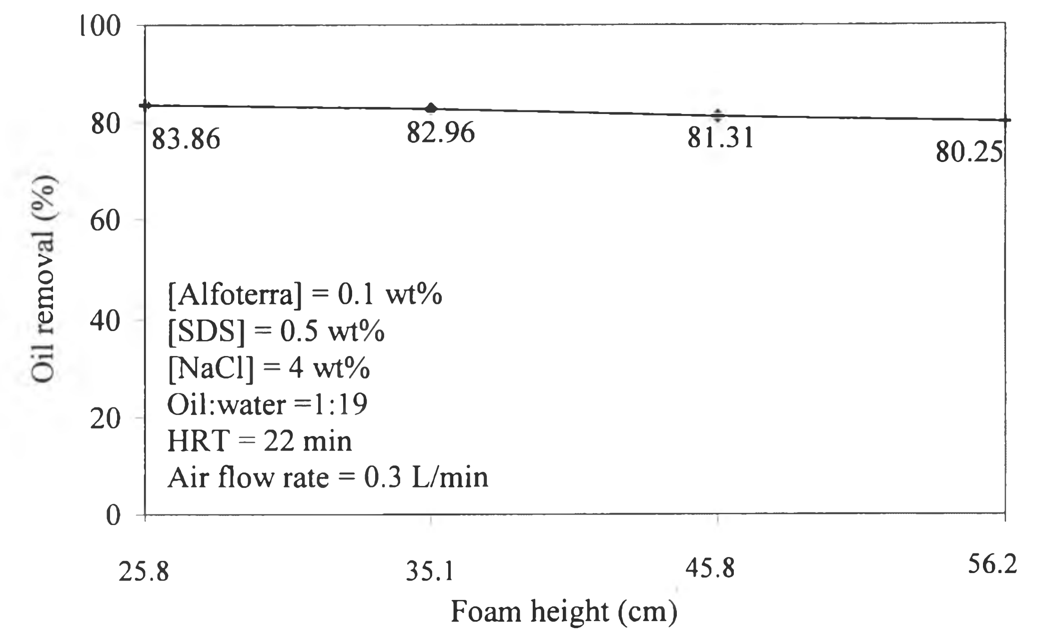

Figure 4.50 Oil removal of system at different foam heights.

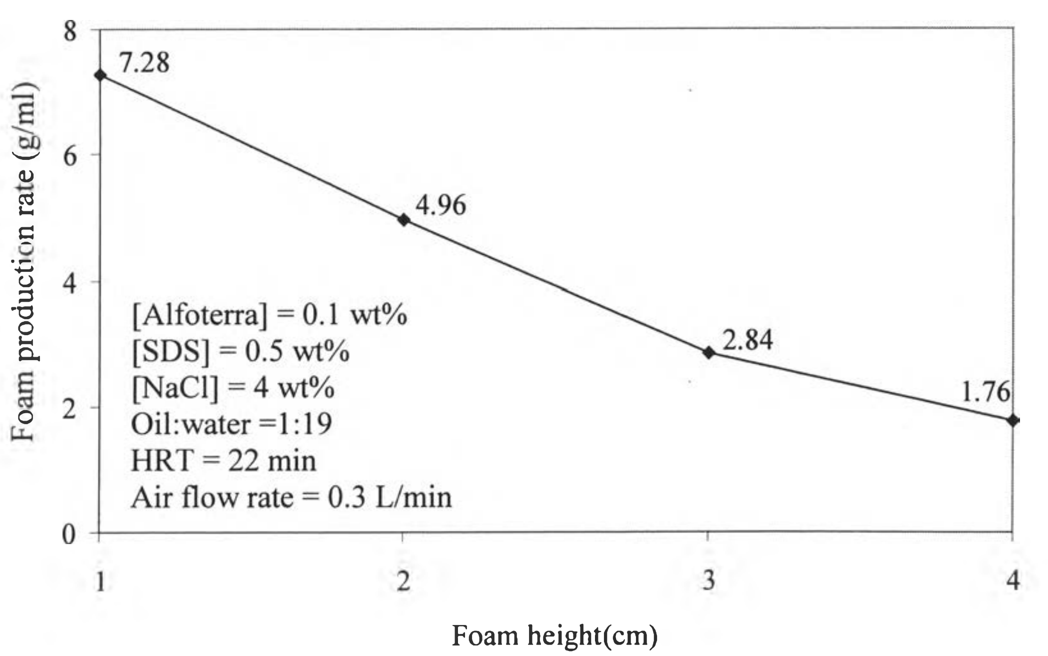

Figure 4.51 Foam production rate of system at different foam heights.

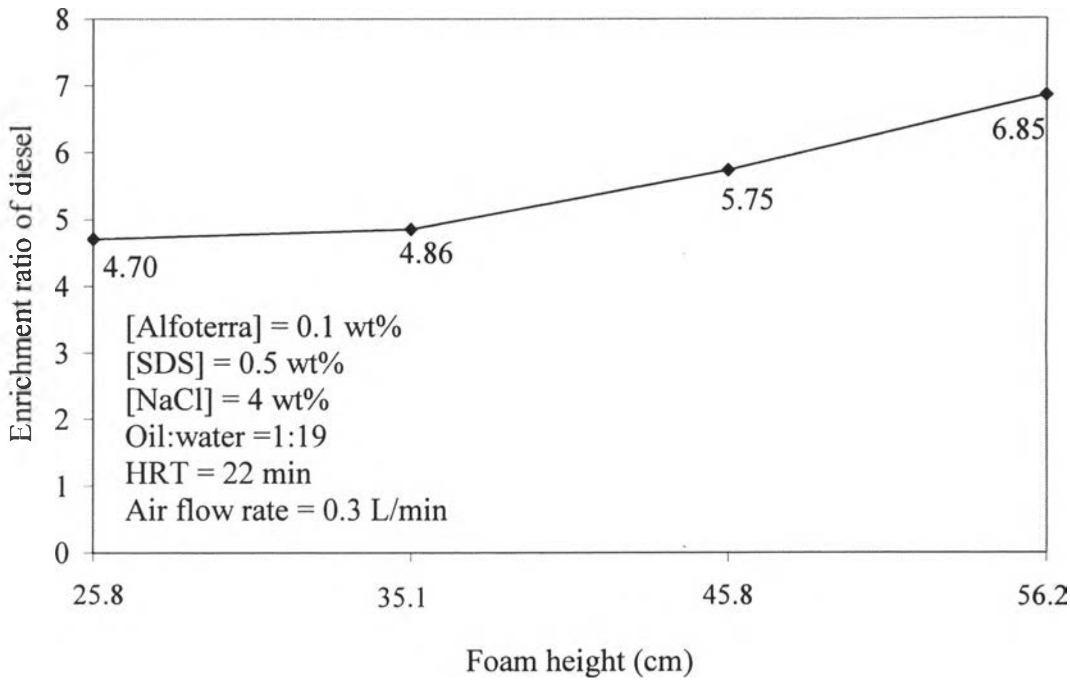

Figure 4.52 Enrichment ratio of diesel of system at different foam heights.

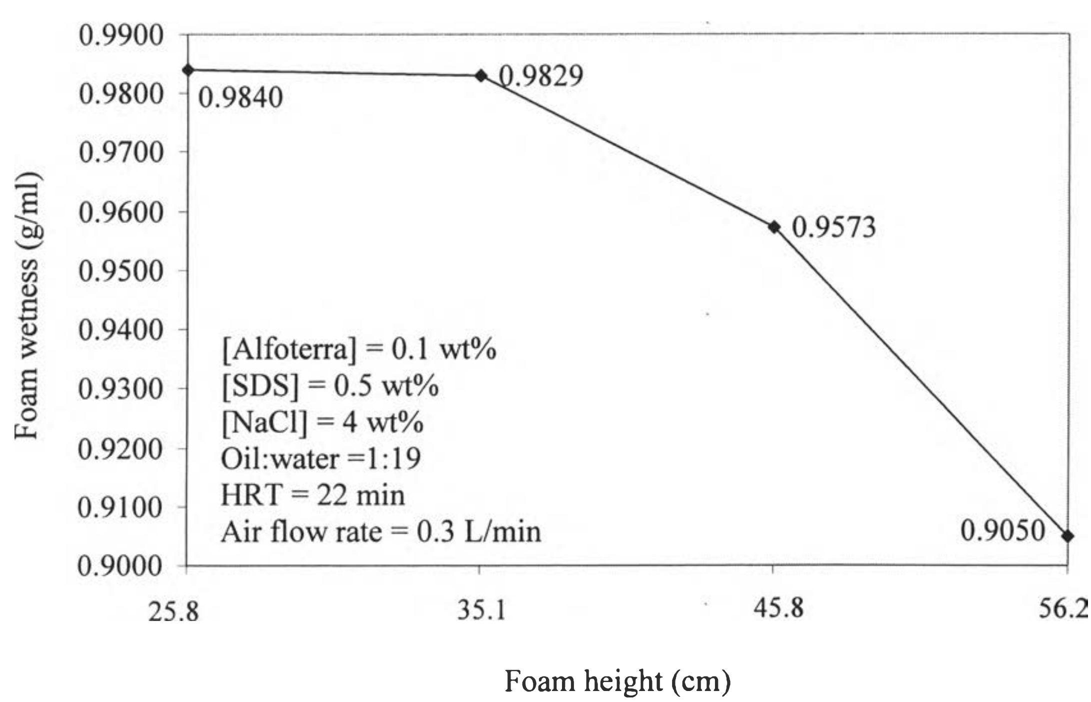

Figure 4.53 Foam wetness of system at different foam heights.

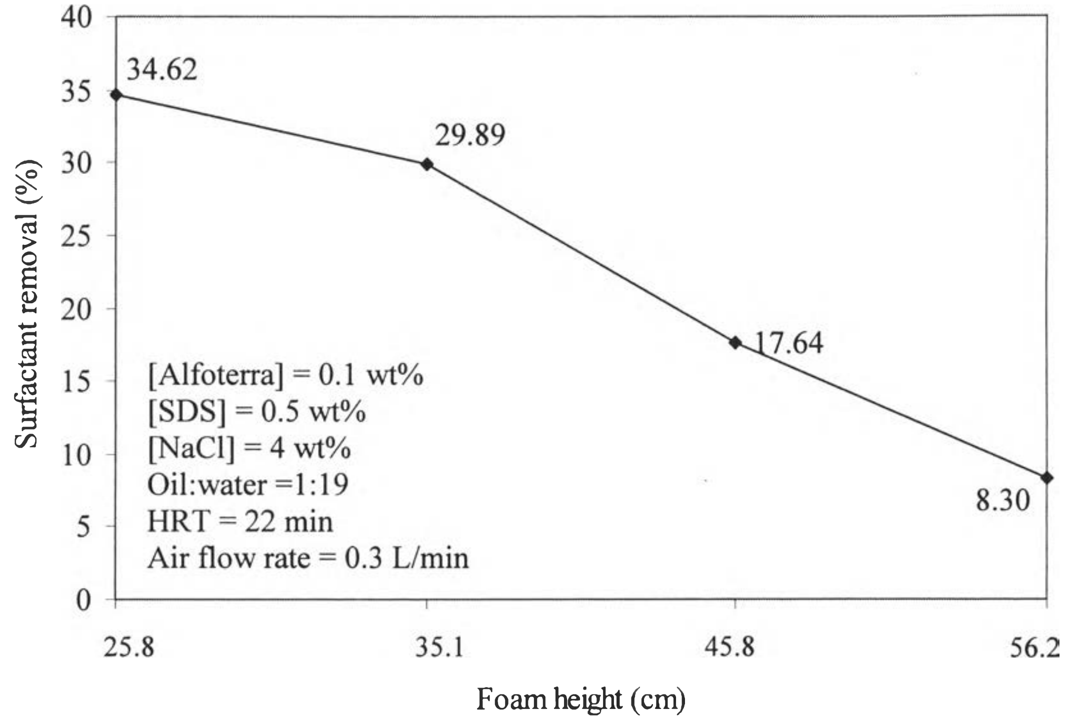

Figure 4.54 Surfactant removal of system at different foam heights.

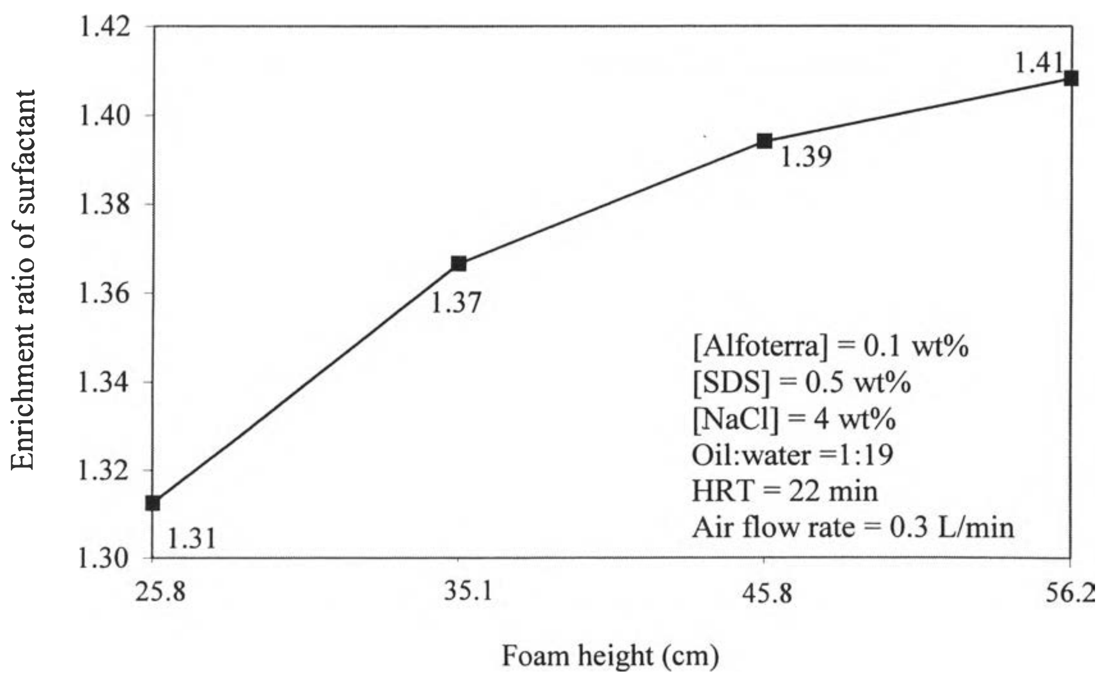

Figure 4.55 Enrichment ratio of surfactant of system at different foam heights.