CHAPTER IV
RESULTS AND DISCUSSION

There are two sections in this research. Firstly, removal of individual heavy metal including cadmium (Cd), copper (Cu), and nickel (Ni). The second section was carried out under mixed heavy metals. Both sections were run using multistage foam fractionation column.

4.1 Operating Limits

A multistage ion foam fractionation unit must be designed properly to allow it to function well. Both air and foam flow only through the bubble caps of the tray. The liquid flows only through the downcomer, not through the bubble caps. The liquid is not wept out through the perforations. The liquid was generated foam at minimum. Finally, air does not bubble up through the downcomers. All of these requirements lead to various operating limits of the multistage ion foam fractionator. In order to have a stable operation of a multistage ion foam fractionation column, both the air and liquid flow rates must be regulated within the proper ranges to meet several requirements. Three important operational conditions— foam formation, flooding, and dumping—are considered to be the constraints of the operation of ion foam fractionation. A sufficient air flow rate is needed in order to produce stable foam to reach the foam outlet at the top tray. The definition of flooding in ion foam fractionation operation is similar to that in a distillation column. The flooding is defined as "excessive accumulation of liquid inside the column". Hence, the flow rate of the effluent is not constant. For any given low or moderate air flow rate, downcomer flooding can occur at very high liquid flow rates. As a result, the liquid level in each tray becomes higher than the overflow weir of the downcomer because of the limitation of the liquid flow through the downcomer. For any given liquid flow rate, entrainment flooding occurs at very high air flow rates, causing some liquid to be carried upward to an upper tray. The last operational problem is dumping. This phenomenon is caused by a low air flow rate. The pressure exerted by the air is insufficient to hold up the liquid on the tray. Therefore, liquid starts to leak through the bubble caps; that is, the liquid on all trays will crash (dump) through to the base of the column.

Figure 4.1 shows the boundaries of the operational zone of the studied multistage ion foam fractionator at a number of stages of 5. When the system is operated at a very low air flow rate, it has a low foam production rate, leading to low removal. However, a longer foam residence time derived from a low air flow rate led to dry foam with a high enrichment ratio. On the other hand, when it is operated at a very high air flow rate, a large fraction of the liquid in the column is transferred into the foam phase, leading to a low enrichment ratio. A high air flow rate, however, results in a high foam production rate and a high mass transfer surface area available for heavy metal ion adsorption, leading to higher removal. When the system is operated at a very high liquid flow rate, the separation efficiency expectedly decreases. This is attributed to a lower residence time of the liquid in the column. Therefore, the optimum conditions, in which both % removal and enrichment ratio are high, should be located far away from the boundary lines, represented by a dash line called the "optimum zone", as depicted in Figure 4.1. With increasing surfactant concentration, the entrainment flooding line tends to shift to lower air flow rates and the downcomer flooding line tends to shift to higher feed flow rates, while the insufficient foaming region tends to be contracted because of higher ability for foam formation. The values of both air flow rate and liquid flow rate located in the operational zone were used to run all experiments in order to avoid all of the operational constraints (dumping, insufficient foam, and flooding).

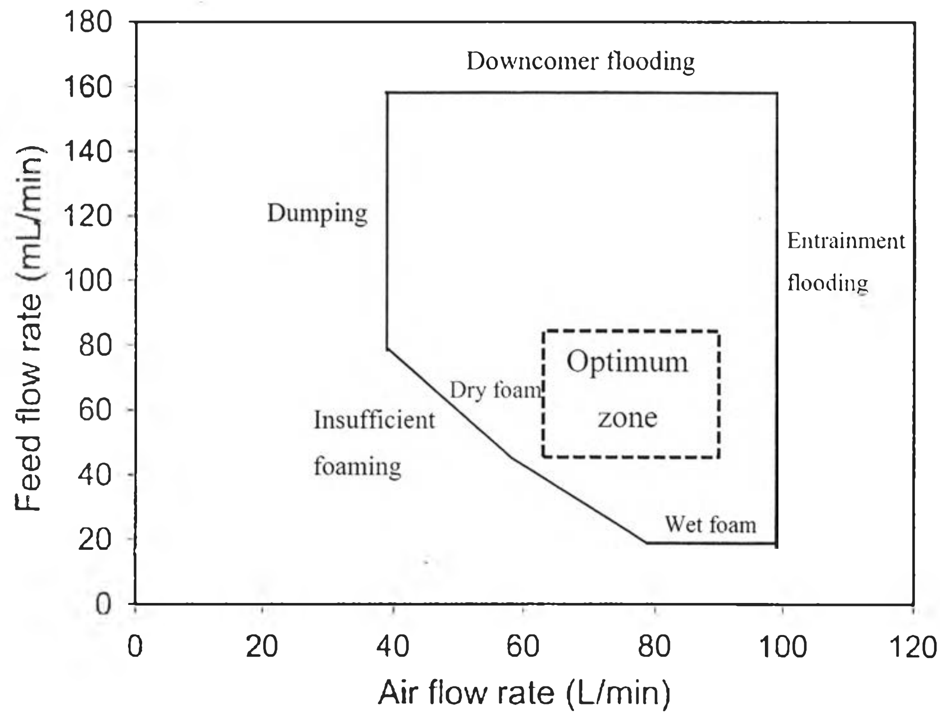


Figure 4.1 Boundaries of the operational zone.

4.2 Removal of Individual Heavy Metal

4.2.1 Removal of Cadmium

4.2.1.1 Effect of Molar Ratio

In a foam fractionation operation, it is necessary that both the enrichment ratios and the removals of SDS and Cd are possible. An increase in surfactant concentration results in increasing removal but wet foam can be undesirably produced, resulting in lowing enrichment ratios. Hence, the effect of feed SDS/Cd molar ratio was investigated in this study. The molar flow rate of a component in a foamate, which is related to the removal of Cd or the SDS recovery, is governed by both adsorptive transport and bulk liquid transport. The adsorptive transport and bulk liquid transport refer to the material transfer by the adsorption on the bubble surface and the entrained liquid in the foam lamella, respectively. The former is an upward stream of the adsorbed materials without carrying liquid while the latter is an upward stream of the lamella liquid with unadsorbed materials. The adsorptive transport can be expressed as $A\Gamma$, the product of flow area (cm^2/min) and surface excess concentration (mol/cm^2). The increase in bulk liquid transport can be affected directly by an enhancement in liquid entrainment in the foam, which is characterized by an increase in the foamate volumetric ratio. This mechanism can reduce the enrichment ratios.

Figure 4.2a shows that an increase in feed SDS/Cd molar ratio decreases the enrichment ratio of Cd. This might be attributed to an increase in the adsorptive transport of Cd resulting from both an increase in the ability for foam formation and the increase in the adsorption density of the SDS-Cd complex with increasing feed SDS/Cd molar ratio.

The SDS separation efficiency in terms of recovery showed same trends of Cd. At a feed SDS/Cd ratio (7/1) or more than are slightly increased the separation efficiency. Moreover, at feed molar ratios below 6/1 that could not generated a sufficientl stable foam, as shown in Figures 4.2b. Because the bulk liquid transport is low at feed SDS/Cd molar ratios below 6/1 as mention above, the separation performance of the SDS should be dominantly governed by the adsorptive transport. These results suggest that the adsorptive transport of the SDS does not increase proportionally to the increasing feed molar flow rate of the SDS, although the adsorption density increases with increasing initial SDS concentration.

Figure 4.2c shows that the separation factor of SDS declines sharply with increasing feed SDS/Cd molar ratio at low feed SDS/Cd molar ratios. This is because of the strong decrease in the enrichment ratio, resulting from the increases in the bulk liquid transport. Interestingly, the separation factor of Cd increased with increasing feed SDS/Cd molar ratio and reached a maximum at a feed SDS/Cd molar ratio of 8/1. The results can be explained in that the foamate volumetric only slightly increased with increasing feed SDS/Cd molar ratio at low feed SDS/Cd molar ratios but increased significantly at high feed SDS/Cd molar ratios. An optimum feed molar ratio of SDS/Cd should be around 8/1 for the studied ion foam fractionation system.

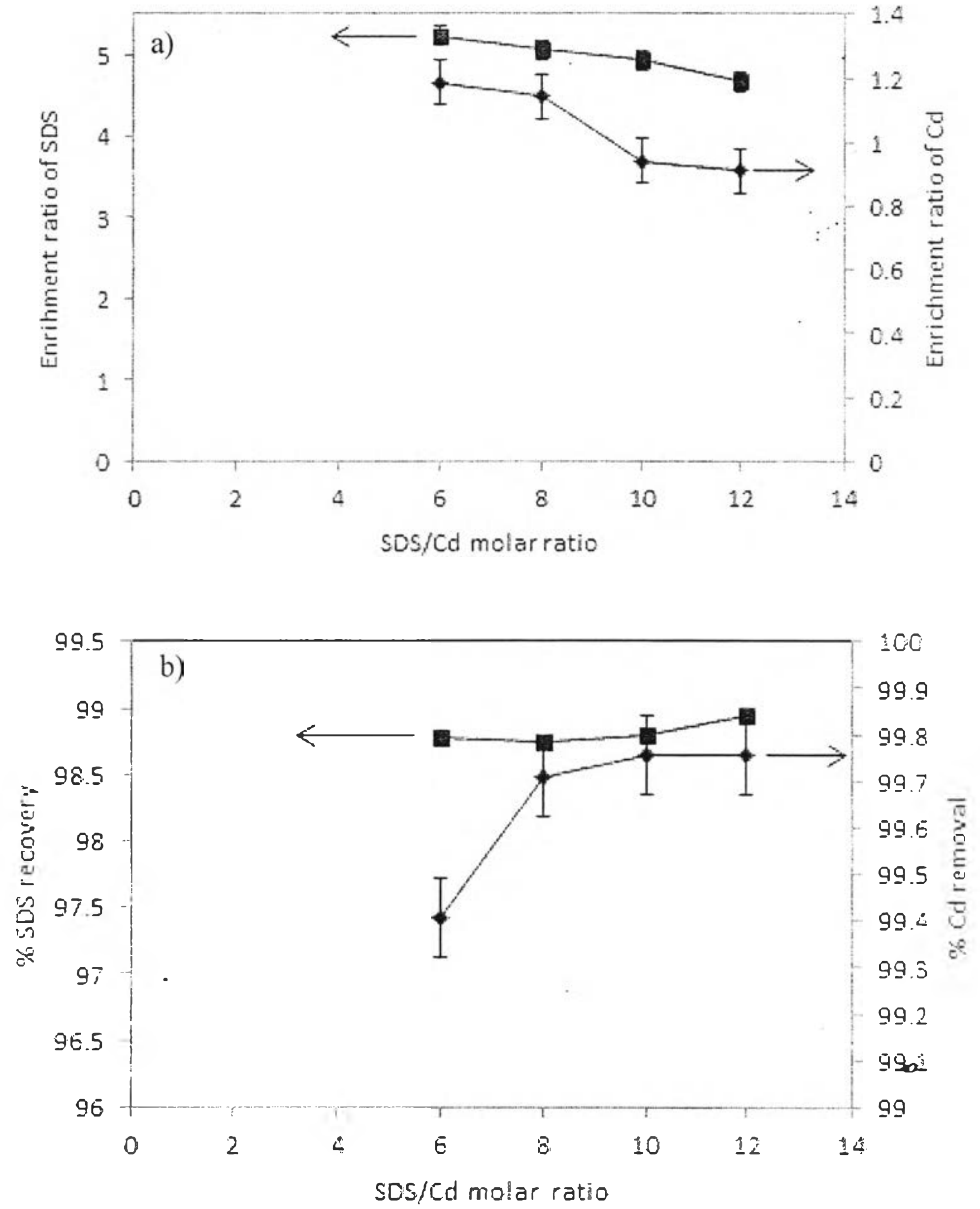


Figure 4.2 Effect of feed SDS/Cd molar ratio on (a) enrichment ratios of SDS and Cd, (b) % SDS recovery and Cd removal, and (c) separation factors of SDS and Cd at an air flow rate of 80 L/min, a feed flow rate of 60 mL/min, a foam height of 60 cm, a feed Cd concentration of 10 mg/L, and the number of trays equal to 5.

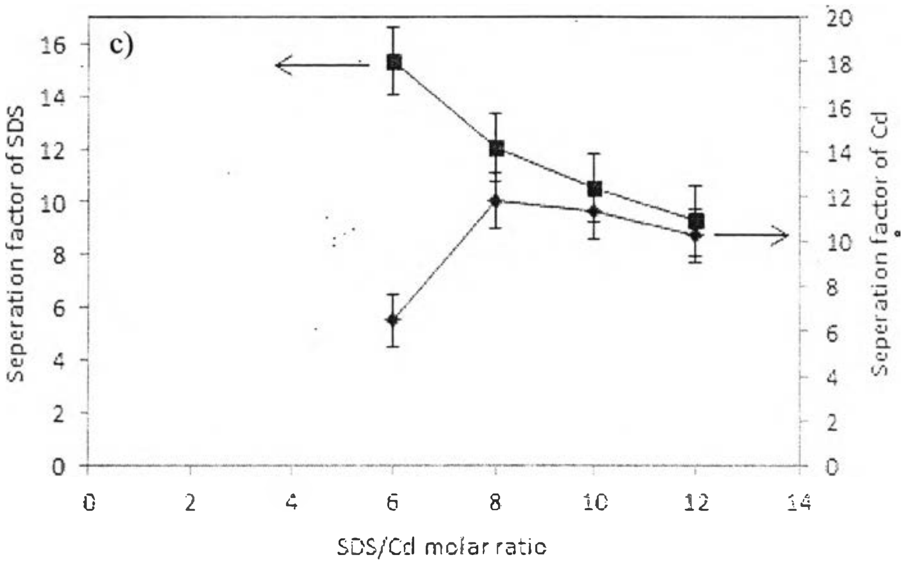


Figure 4.2 Effect of feed SDS/Cd molar ratio on (a) enrichment ratios of SDS and Cd, (b) % SDS recovery and Cd removal, and (c) separation factors of SDS and Cd at an air flow rate of 80 L/min, a feed flow rate of 60 mL/min, a foam height of 60 cm, a feed Cd concentration of 10 mg/L, and the number of trays equal to 5. (con't.)

4.2.1.2 Effect of Foam Height

Both air and liquid flow rates must be in appropriate ranges in order to successfully operate an multistage foam fractionation system. The operational zone of the studied unit for multistage ion foam fractionation. In this section, an air flow rate of 80 dm^3/min and a feed flow rate of 60 mL/min, located in the operational zone, were selected to run the multistage ion foam fractionation column in order to observe the effect of foam height on separation efficiency. A lowest feed SDS/Cd molar ratio of 8/1 was found to be necessary to produce stable foam proficient reaching to reach a foam height of 90 cm.

For any given feed SDS/Cd molar ratio, an increase in foam height results in an enhancement in the enrichment ratios of both SDS and Cd, especially at the highest foam height (90 cm), as shown in Figure 4.3a. This is because the increase in foam height increases the foam residence time, which allows more drainage of the liquid in the foam films. This decrease suggests that the bulk liquid transport is reduced with increasing foam height. The effect of feed SDS/Cd molar ratio on the reduction in the enrichment ratios was much more profound at the higher foam height of 90 cm as compared to the lower foam height of 30 cm and 60 cm. The results can be explained by the fact that the foamate volumetric decreased significantly with increasing foam height. This is most likely because Gibbs–Marangoni effects are suppressed at high bulk surfactant concentrations, leading to a very high liquid drainage rates in the produced foam.

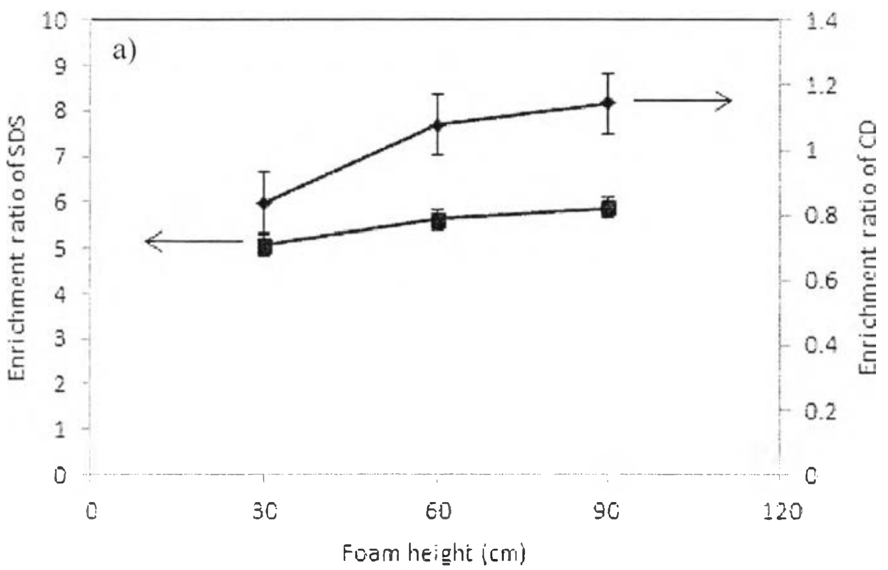


Figure 4.3 Effect of foam height on (a) the enrichment ratios of Cd and SDS; (b) SDS recovery and Cd removal; and (c) the separation factors of SDS and Cd at air flow rate = 80 dm^3/min, feed flow rate = 60 mL/min, number of trays =5, feed Cd concentration = 10 mg/L, and a feed SDS/Cd molar ratios of 8/1.

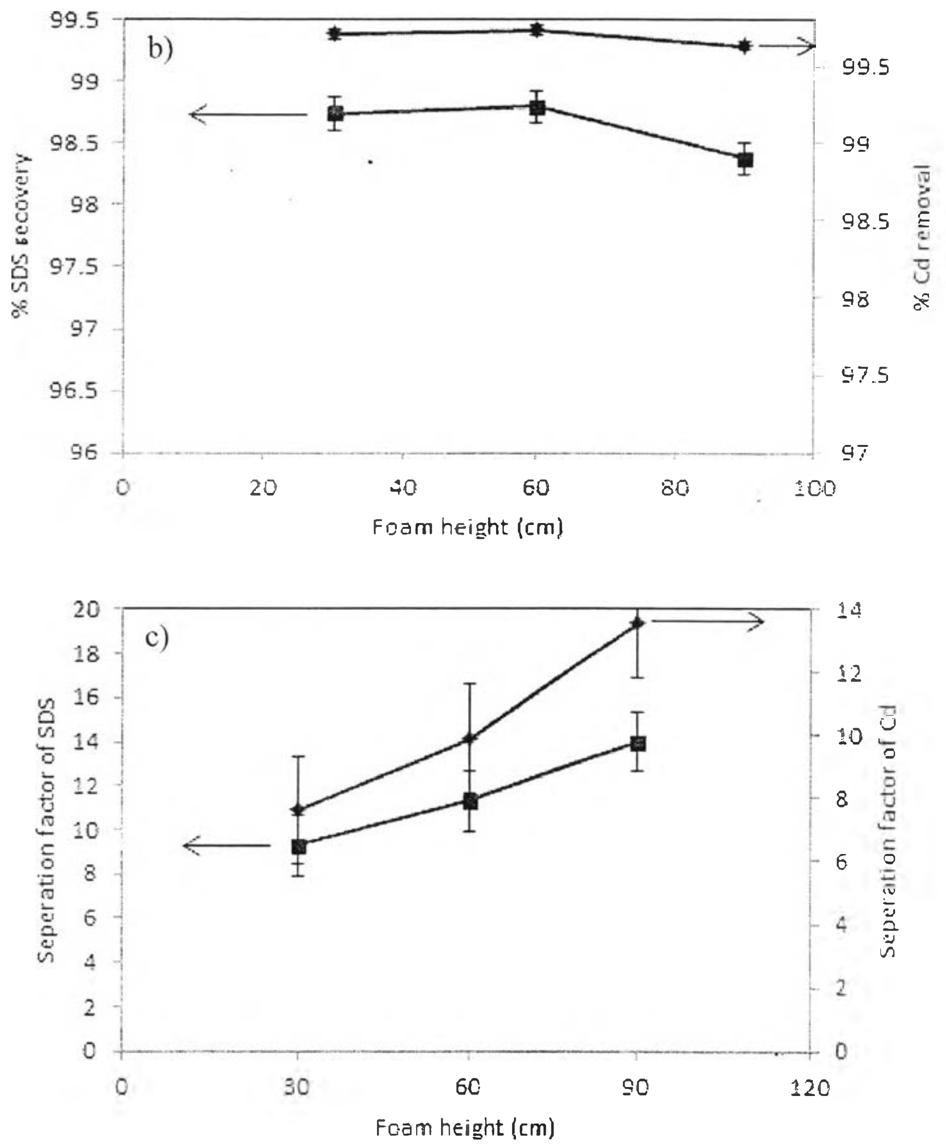


Figure 4.3 Effect of foam height on (a) the enrichment ratios of Cd and SDS; (b) SDS recovery and Cd removal; and (c) the separation factors of SDS and Cd at air flow rate = 80 dm^3/min, feed flow rate = 60 mL/min, number of trays =5, feed Cd concentration = 10 mg/L, and a feed SDS/Cd molar ratios of 8/1. (con't.)

The reduction in SDS recovery was found to be more pronounced for the system because of the larger decrease in foamate volumetric.

However, the Cd removal almost remain unchanged with increasing foam height, as shown in Figures 4.3b. These results indicate that the draining liquid contains an insignificant amount of unadsorbed Cd while most Cd ions co-adsorb with the SDS onto the foam interface. Hence, a reduction of the bulk liquid transport does not decrease the molar flow rate of Cd in the foamate and does not significantly increase the concentration of Cd in the effluent. From the results, it can be concluded that the molar flow rate of Cd in the foamate is mainly governed by adsorptive transport.

This suggests that, with increasing foam height, a decrease in the contribution of the bulk liquid transport of SDS to the molar flow rate of SDS in foamate becomes significant. At the lowest foam height of 30 cm, the system generated wet foam, which contains a larger amount of bulk liquid with relatively high SDS concentration and a lower Cd concentration than those of dry foam. At the highest foam height of 90 cm, the foam is extremely dry and the effect of the bulk liquid transport on the molar ratio of SDS/Cd in the foamate is less pronounced.

Figure 4.3c shows the effects of foam height on the separation factors of SDS and Cd. The separation factors showed to have the same trend as the enrichment ratios for both Cd and SDS. The separation factors of both were enhanced with increasing foam height due to the increase in liquid film drainage (the reduction of bulk liquid transport). The effect of foam height became more prominent as the foam height increased from 60 to 90 cm. These results suggest that the liquid film drainage is an important mechanism for enhancing separation efficiency in a foam fractionation process.

4.2.1.3 Effect of Air Flow Rate

The effect of air flow rate on the separation efficiency of the studied multistage ion foam fractionation system was investigated by varying the air flow rate in the range of 40 to 100 dm^3/min, while the other operational parameters were fixed at a feed flow rate of 60 mL/min, a foam height of 60 cm, the number of trays at 5. The lowest feed SDS/Cd molar ratio of 8/1 was used to operate the studied multistage ion foam fractionation unit because it could produce sufficiently stable foam. The enrichment ratios of both SDS and Cd decrease with increasing air flow rate, as shown in Figure 4.4a. The results can be explained by the fact that the foamate volumetric ratio increased with increasing air flow rate. This increase in foamate volumetric indicates an increase in the bulk liquid transport. As a consequence, the foamate contained more water fraction and less SDS and Cd concentrations, leading to lowering enrichment ratios.

As shown in Figure 4.4b, both SDS recovery and Cd removal increase with increasing air flow rate for both feed SDS/Cd molar ratios. The increase in Cd removal with increasing air flow rate from 40 to 60 dm^3/min is due to the increase in the adsorptive transport. The small increase in Cd removal with increasing air flow rate beyond 60 dm^3/min, indicating the increase in the bulk liquid transport because increase in volume of foamate. However, the increase in SDS recovery with increasing air flow rate is due to both mechanisms. This explanation can be also supported by the fact that the profile of SDS recovery mirrors that of the volumetric ratio, that define is volume of foamate to volume of feed, as shown in Figures 4.4b. The molar ratio of SDS/Cd in the foamate increased with increasing air flow rate and it mirrored the foamate volumetric ratio, suggesting that an increasing air flow rate can increase both adsorptive and bulk liquid transport and, at very high air flow rates, the bulk liquid transport becomes predominantly. However, at an extremely high air flow rate, the system cannot produce stable foam (as explained later), causing the system to reach a maximum separation performance.

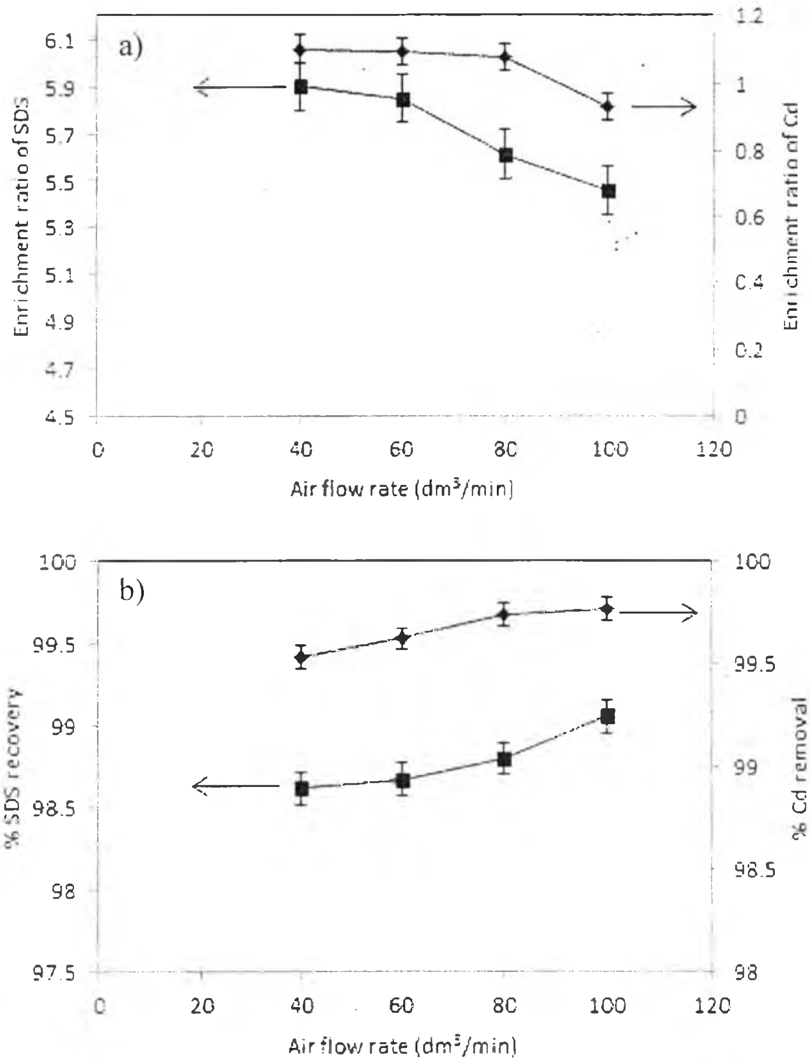


Figure 4.4 Effect of air flow rate on the enrichment ratios of Cd and SDS (a); SDS recovery and Cd removal (b); and the separation factors of SDS and Cd (c) at foam height = 60 cm, feed flow rate = 60 mL/min, number of trays = 5, feed Cd concentration = 10 mg/L, and a feed molar ratios of SDS/Cd of 8/1.

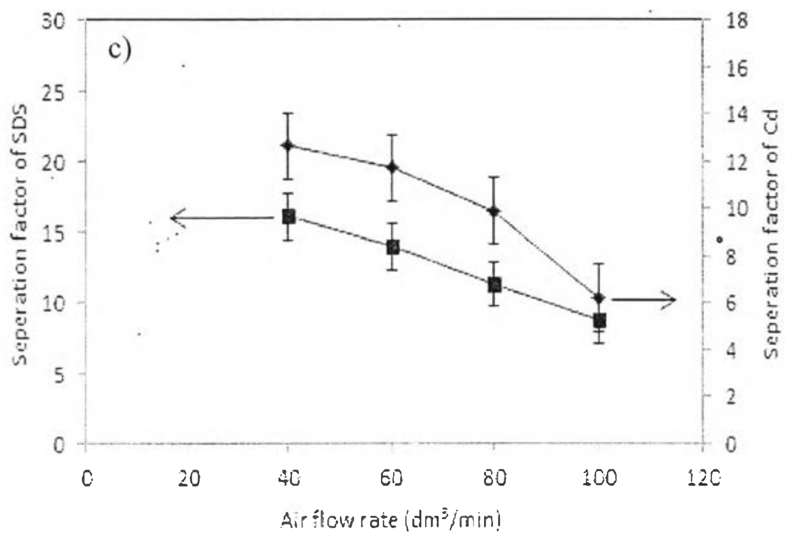


Figure 4.4 Effect of air flow rate on the enrichment ratios of Cd and SDS (a); SDS recovery and Cd removal (b); and the separation factors of SDS and Cd (c) at foam height = 60 cm, feed flow rate = 60 mL/min, number of trays = 5, feed Cd concentration = 10 mg/L, and a feed molar ratios of SDS/Cd of 8/1. (con't.)

Figure 4.4c shows the effect of air flow rate on the separation factors of SDS and Cd. The separation factors of SDS and Cd tended to decrease with increasing air flow rate and reached minimum at high air flow rates. Therefore, focusing on Cd removal, the air flow rate of 80 dm^3/min seems to provide both reasonably high Cd removal with high SDS recovery for this studied feed SDS/Cd molar ratios even though the enrichment ratios and separation factors were low. Hence, this air flow rate of 80 dm^3/min was selected to investigate the effect of feed flow rate.

4.2.1.4 Effect of Feed Flow Rate

The effect of feed flow rate on separation efficiency was investigated by varying the feed flow rate in the range of 40 to 100 dm^3/min, while the other operational parameters were fixed at a feed flow rate of 60 mL/min, a foam height of 60 cm, the number of trays at 5. The lowest feed SDS/Cd molar ratio of 8/1 was used to operate the studied multistage ion foam fractionation unit because it could produce sufficiently stable foam.

In this condition, the enrichment ratios of both SDS and Cd changed slightly with increasing feed flow rate. This is because the foamate volumetric ratio decreases slightly with increasing feed flow rate, as shown in Figure 4.5a. As a result, the enrichment ratios of both SDS and Cd did not change with feed flow rate, indicating that the system performance is governed by adsorptive transport.

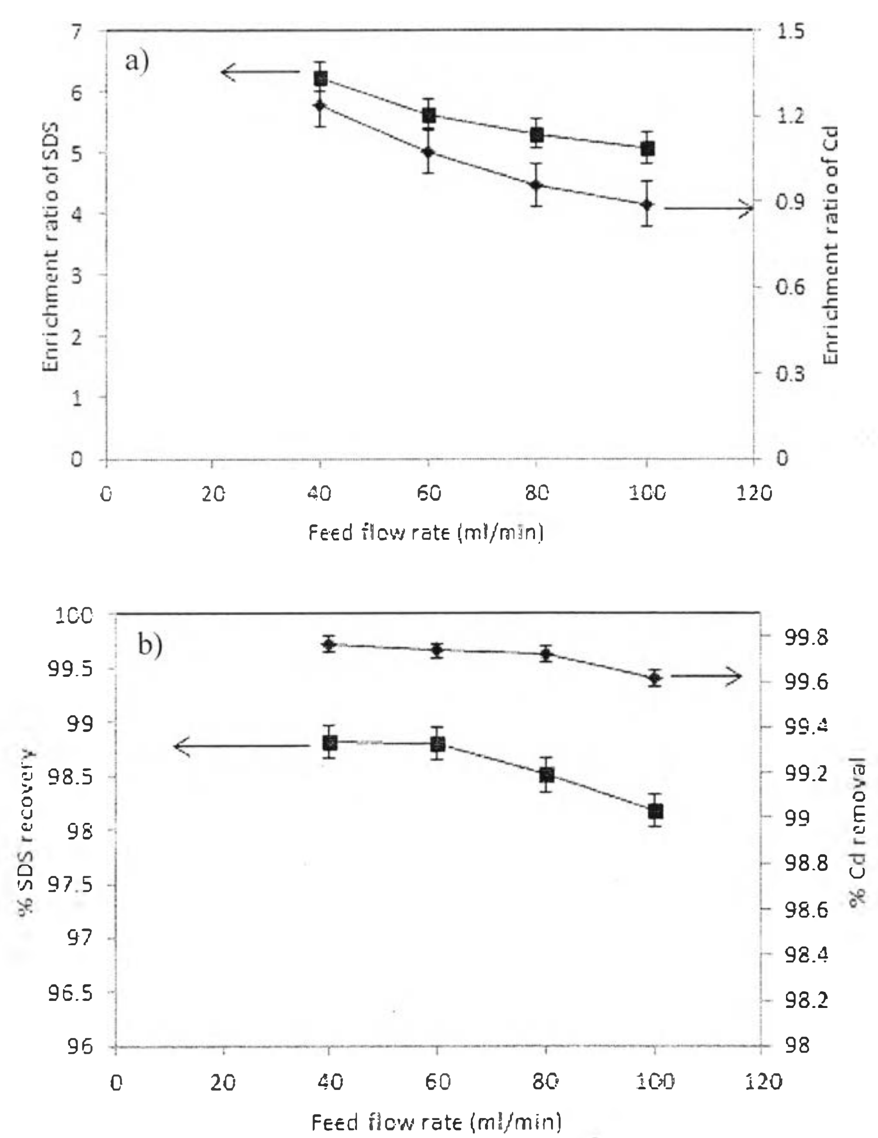


Figure 4.5 Effect of feed flow rate on the enrichment ratios of Cd and SDS (a); SDS recovery and Cd removal (b); and the separation factors of SDS and Cd (c) at foam height = 60 cm, air flow rate = 60 dm^3/min, SDS/Cd = 8/1, feed Cd concentration = 10 mg/L, and number of trays = 5

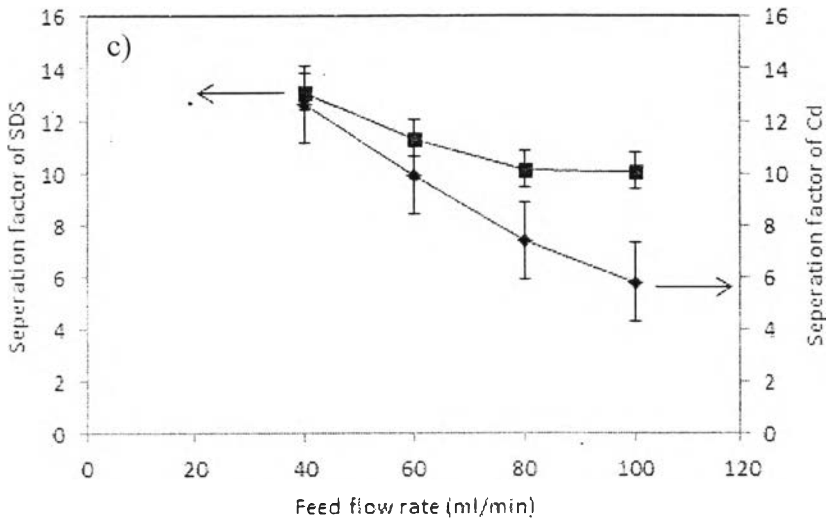


Figure 4.5 Effect of feed flow rate on the enrichment ratios of Cd and SDS (a); SDS recovery and Cd removal (b); and the separation factors of SDS and Cd (c) at foam height = 60 cm, air flow rate = 60 dm^3/min, SDS/Cd = 8/1, feed Cd concentration = 10 mg/L, and number of trays = 5 (con't.)

Under steady state condition, the Cd removal and SDS recovery can be related to the molar flow rates of Cd and SDS in foamate, respectively, resulting from both adsorptive and bulk liquid transports. The SDS recovery and Cd removal decreased with increasing feed flow rate, as shown in Figure 4.5b. These results suggest that the increasing bulk liquid transport (wet foam condition) provides an unequal degree of bulk liquid transport between Cd and SDS, especially at high feed flow rates. The SDS recovery is promoted predominantly by the increase in bulk liquid transport as compared with the Cd removal because the entrained liquid contains predominantly SDS with a very small amount of Cd and most Cd ions adsorb preferentially at the foam surface. In other word, the Cd removal is not promoted by the increasing bulk liquid transport (wet foam condition) but is mainly governed by the adsorptive transport .

As shown in Figure 4.5c, the separation factors of both SDS and Cd decrease markedly with increasing feed flow rate because the bulk liquid transport has to be minimized in order to achieve maximum separation factors of both SDS and Cd. A feed flow rate of 60 mL/min was selected for further investigation because it was the highest feed flow rate to provide sufficiently high Cd removal.

4.2.2 Removal of Copper

4.2.2.1 Effect of Molar Ratio

Figure 4.6a shows that an increase in feed SDS/Cu molar ratio decreases the enrichment ratio of Cu. This might be attributed to an increase in the adsorptive transport of Cu resulting from both an increase in the ability for foam formation and the increase in the adsorption density of the SDS-Cu complex with increasing feed SDS/Cu molar ratio.

The SDS separation efficiency in terms of recovery showed same trends of Cu. At a feed SDS/Cd ratio (7/1) or more than are slightly increased the separation efficiency. Moreover, at feed molar ratios below 6/1 that could not generated a sufficientl stable foam, as shown in Figures 4.6b. Because the bulk liquid transport is low at feed SDS/Cu molar ratios below 6/1 as mention above, the separation performance of the SDS should be dominantly governed by the adsorptive transport. These results suggest that the adsorptive transport of the SDS does not increase proportionally to the increasing feed molar flow rate of the SDS, although the adsorption density increases with increasing initial SDS concentration.

Figure 4.6c shows that the separation factor of SDS declines sharply with increasing feed SDS/Cu molar ratio at low feed SDS/Cu molar ratios. This is because of the strong decrease in the enrichment ratio, resulting from the increases in the bulk liquid transport. The results can be explained in that the foamate volumetric only slightly increased with increasing feed SDS/Cu molar ratio at low feed SDS/Cu molar ratios but increased significantly at high feed SDS/Cu molar ratios. An optimum feed molar ratio of SDS/Cu should be around 8/1 for the studied ion foam fractionation system.

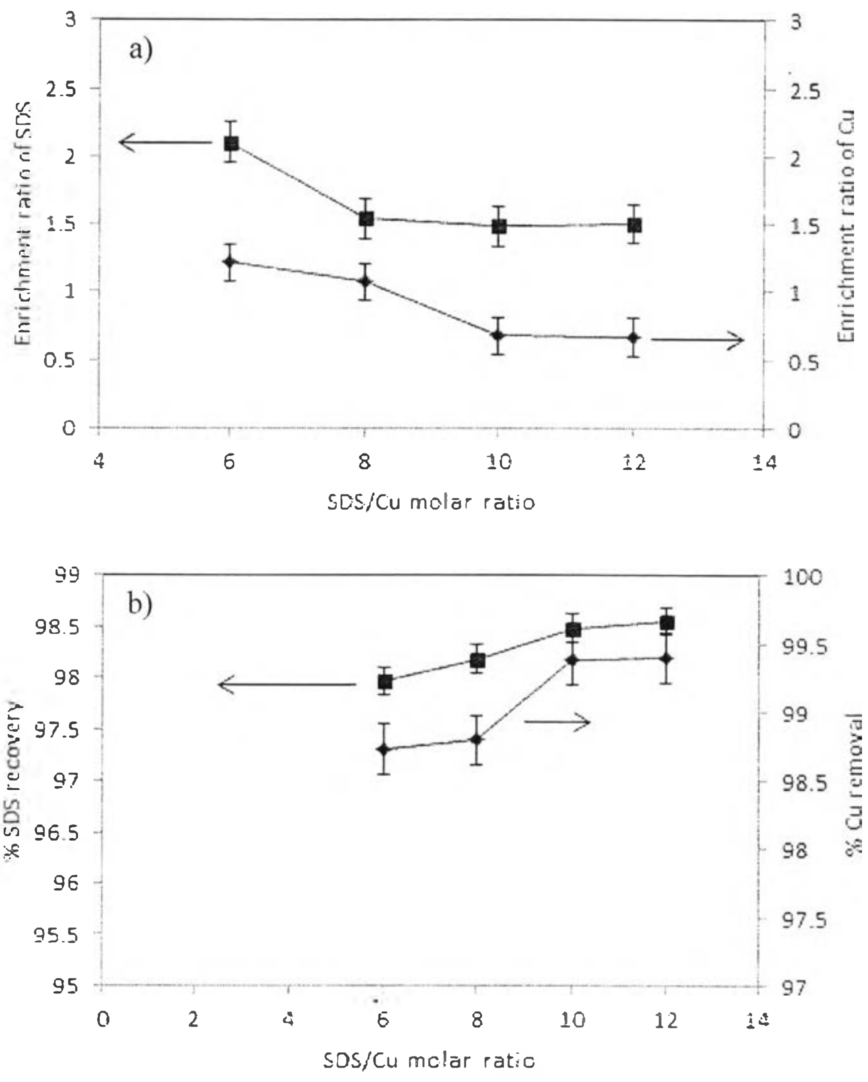


Figure 4.6 Effect of feed SDS/Cu molar ratio on (a) enrichment ratios of SDS and Cu, (b) % SDS recovery and Cu removal, and (c) separation factors of SDS and Cu at an air flow rate of 80 L/min, a feed flow rate of 60 mL/min, a foam height of 60 cm, a feed Cu concentration of 10 mg/L, and the number of trays equal to 5.

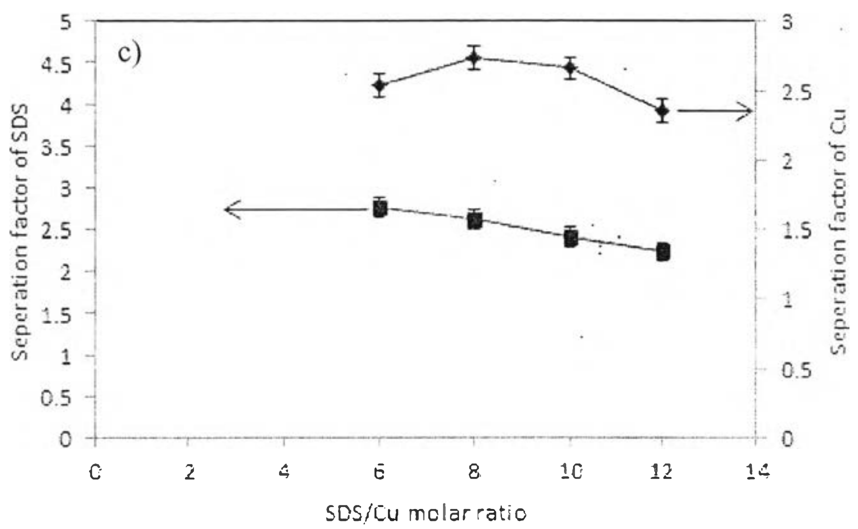
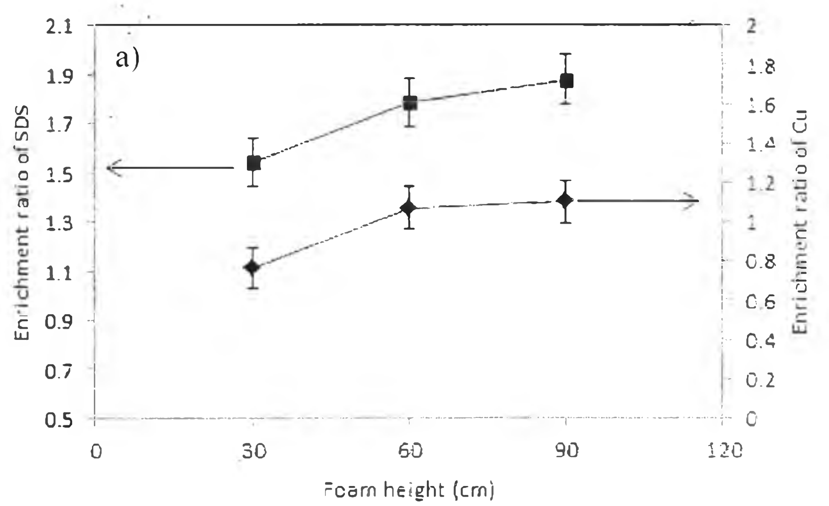


Figure 4.6 Effect of feed SDS/Cu molar ratio on (a) enrichment ratios of SDS and Cu, (b) % SDS recovery and Cu removal, and (c) separation factors of SDS and Cu at an air flow rate of 80 L/min, a feed flow rate of 60 mL/min, a foam height of 60 cm, a feed Cu concentration of 10 mg/L, and the number of trays equal to 5. (con't.)

4.2.2.2 Effect of Foam Height

In this section, an air flow rate of 80 dm^3/min and a feed flow rate of 60 mL/min were selected to run the multistage ion foam fractionation column. A lowest feed SDS/Cu molar ratio of 8/1 was found to be necessary to produce stable foam proficient reaching to reach a foam height of 90 cm.

An increase in foam height results in an enhancement in the enrichment ratios of both SDS and Cu, especially at the highest foam height (90 cm), as shown in Figure 4.7a. This is because the increase in foam height increases the foam residence time, which allows more drainage of the liquid in the foam films, as indicated by the large decrease in foamate volumetric ratio with increasing foam height. This decrease suggests that the bulk liquid transport is reduced with increasing foam height. The effect of feed SDS/Cu molar ratio on the reduction in the enrichment ratios was much more profound at the higher foam height of 90 cm as compared to the lower foam height of 30 cm and 60 cm. The results can be explained by the fact that the foamate volumetric ratio decreased significantly with increasing foam height. This is most likely because Gibbs–Marangoni effects are suppressed at high bulk surfactant concentrations, leading to a very high liquid drainage rates in the produced foam.



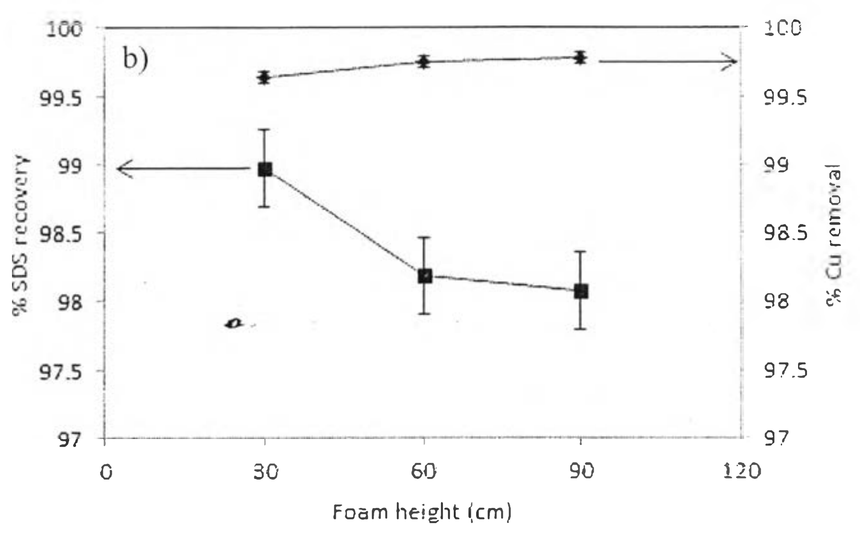


Figure 4.7 Effect of foam height on (a) the enrichment ratios of Cu and SDS; (b) SDS recovery and Cu removal; and (c) the separation factors of SDS and Cu at air flow rate = 80 dm^3/min, feed flow rate = 60 mL/min, number of trays =5, feed Cu concentration = 10 mg/L, and a feed SDS/Cu molar ratios of 8/1.

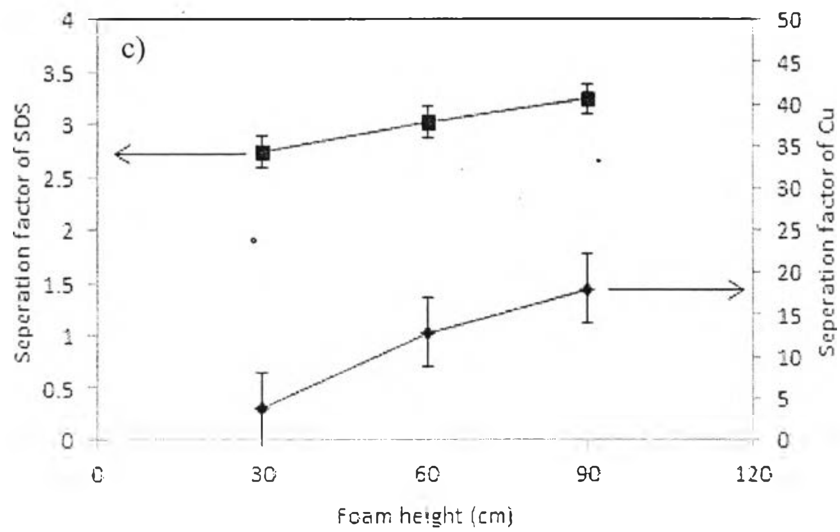


Figure 4.7 Effect of foam height on (a) the enrichment ratios of Cu and SDS; (b) SDS recovery and Cu removal; and (c) the separation factors of SDS and Cu at air flow rate = 80 dm^3/min, feed flow rate = 60 mL/min, number of trays =5, feed Cu concentration = 10 mg/L, and a feed SDS/Cu molar ratios of 8/1. (con't.)

The reduction in SDS recovery was found to be decreased at foam height 60 cm because of the larger decrease in foamate volumetric ratio.

However, the Cu removal almost slightly changed with increasing foam height, as shown in Figures 4.7b. These results indicate that the draining liquid contains an insignificant amount of unadsorbed Cu while most Cu ions co-adsorb with the SDS onto the foam interface. Hence, a reduction of the bulk liquid transport does not decrease the molar flow rate of Cu in the foamate and does not significantly increase the concentration of Cu in the effluent. From the results, it can be concluded that the molar flow rate of Cu in the foamate is mainly governed by adsorptive transport.

Moreover, an increasing foam height, a decrease in the contribution of the bulk liquid transport of SDS to the molar flow rate of SDS in foamate becomes significant. At the lowest foam height of 30 cm, the system generated wet foam, which contains a larger amount of bulk liquid with relatively high SDS concentration and a lower Cu concentration than those of dry foam. At the highest foam height of

90 cm, the foam is extremely dry and the effect of the bulk liquid transport on the molar ratio of SDS/Cu in the foamate is less pronounced.

Figure 4.7c shows the effects of foam height on the separation factors of SDS and Cu. The separation factors showed to have the same trend as the enrichment ratios for both Cu and SDS. The separation factors of both were enhanced with increasing foam height due to the increase in liquid film drainage (the reduction of bulk liquid transport). The effect of foam height became more prominent as the foam height increased from 60 to 90 cm. These results suggest that the liquid film drainage is an important mechanism for enhancing separation efficiency in a foam fractionation process.

4.2.2.3 Effect of Air Flow Rate

The effect of air flow rate was investigated by varying the air flow rate in the range of 40 to 100 dm^3/min, while the other operational parameters were fixed at a feed flow rate of 60 mL/min, a foam height of 60 cm, the number of trays at 5. The lowest feed SDS/Cu molar ratio of 8/1 was used to operate the studied multistage ion foam fractionation unit because it could produce stable foam. The enrichment ratios of both SDS and Cu decrease with increasing air flow rate, as shown in Figure 4.8a. The results can be explained by the fact that the foamate volumetric ratio increased with increasing air flow rate. This increase in foamate volumetric ratio indicates an increase in the bulk liquid transport. As a consequence, the foamate contained more water fraction and less SDS and Cd concentrations, leading to lowering enrichment ratios.

As shown in Figure 4.8b, both SDS recovery and Cu removal increase with increasing air flow rate for both feed SDS/Cu molar ratios. Because the increase in the adsorptive transport. The small increase in Cu removal with increasing air flow rate beyond 60 dm^3/min, indicating the increase in the bulk liquid transport because increase in volume of foamate. At below 60 dm^3/min, foam could not generate. However, the increase in SDS recovery with increasing air flow rate is due to both mechanisms. This explanation can be also supported by the fact that the profile of SDS recovery mirrors that of the volumetric ratio, that define is volume of foamate to volume of feed, as shown in Figures 4.8b. The molar ratio of SDS/Cu in the foamate increased with increasing air flow rate and it mirrored the foamate volumetric ratio, suggesting that an increasing air flow rate can increase both adsorptive and bulk liquid transport and, at very high air flow rates, the bulk liquid transport becomes predominantly. However, at an extremely high air flow rate, the system cannot produce stable foam, causing the system to reach a maximum separation performance.

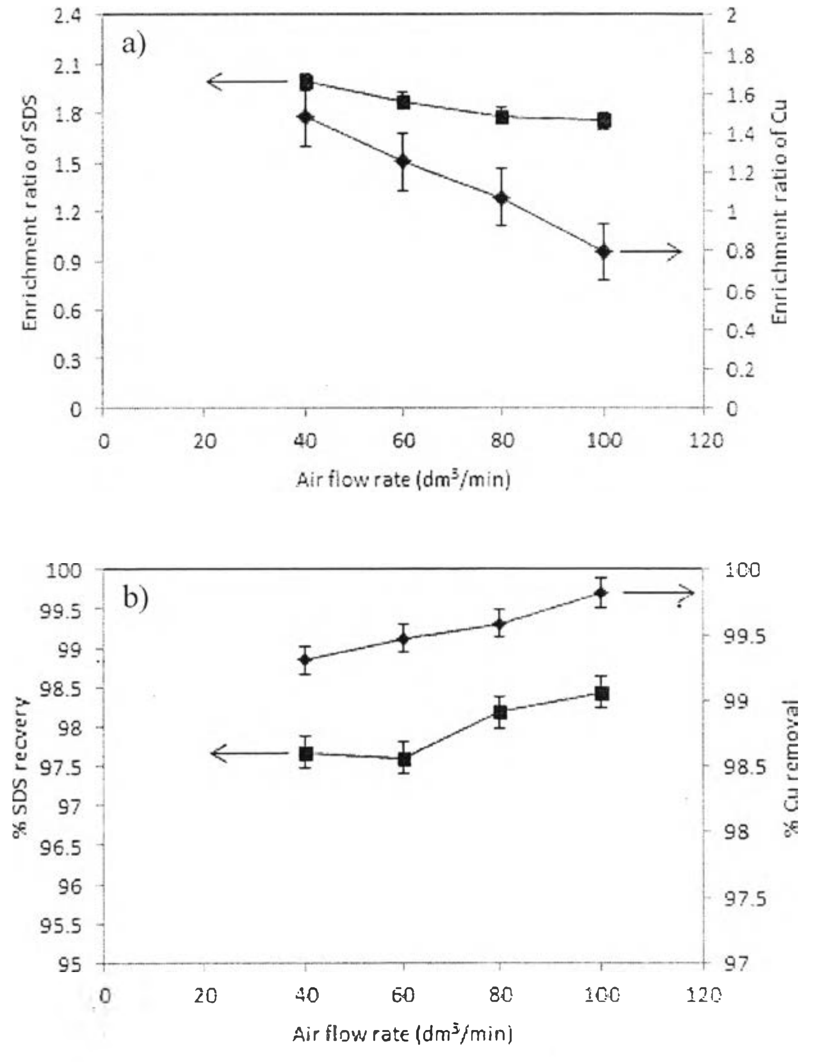


Figure 4.8 Effect of air flow rate on the enrichment ratios of Cu and SDS (a); SDS recovery and Cu removal (b); and the separation factors of SDS and Cu (c) at foam height = 60 cm, feed flow rate = 60 mL/min, number of trays = 5, feed Cu concentration = 10 mg/L, and a feed molar ratios of SDS/Cu of 8/1.

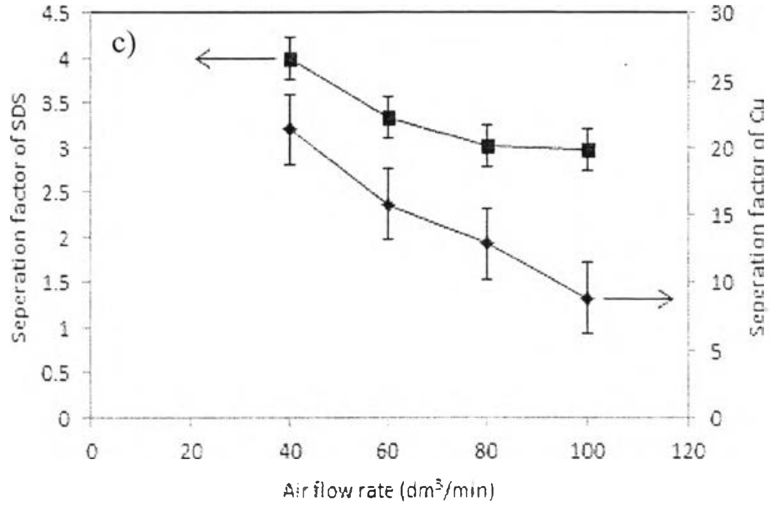


Figure 4.8 Effect of air flow rate on the enrichment ratios of Cu and SDS (a); SDS recovery and Cu removal (b); and the separation factors of SDS and Cu (c) at foam height = 60 cm, feed flow rate = 60 mL/min, number of trays = 5, feed Cu concentration = 10 mg/L, and a feed molar ratios of SDS/Cu of 8/1. (con't.)

Figure 4.8c shows the effect of air flow rate on the separation factors of SDS and Cu. The separation factors of SDS and Cu tended to decrease with increasing air flow rate and reached minimum at high air flow rates. Therefore, focusing on Cu removal, the air flow rate of 80 dm^3/min seems to provide both reasonably high Cu removal with high SDS recovery for this studied feed SDS/Cu molar ratios even though the enrichment ratios and separation factors were low. Hence, this air flow rate of 80 dm^3/min was selected to investigate the effect of feed flow rate.

4.2.2.4 Effect of Feed Flow Rate

The effect of feed flow rate on separation efficiency was investigated by varying the feed flow rate in the range of 40 to 100 dm^3/min, while the other operational parameters were fixed at a feed flow rate of 60 mL/min, a foam height of 60 cm, the number of trays at 5. The lowest feed SDS/Cu molar ratio of 8/1 was used to operate the studied multistage ion foam fractionation unit because it could produce sufficiently stable foam.

In this condition, the enrichment ratios of both SDS and Cu decreased slightly with increasing feed flow rate. This is because the foamate volumetric ratio decreases slightly with increasing feed flow rate, as shown in Figure 4.9a. As a result, the enrichment ratios of both SDS and Cu did not change with feed flow rate, indicating that the system performance is governed by adsorptive transport.

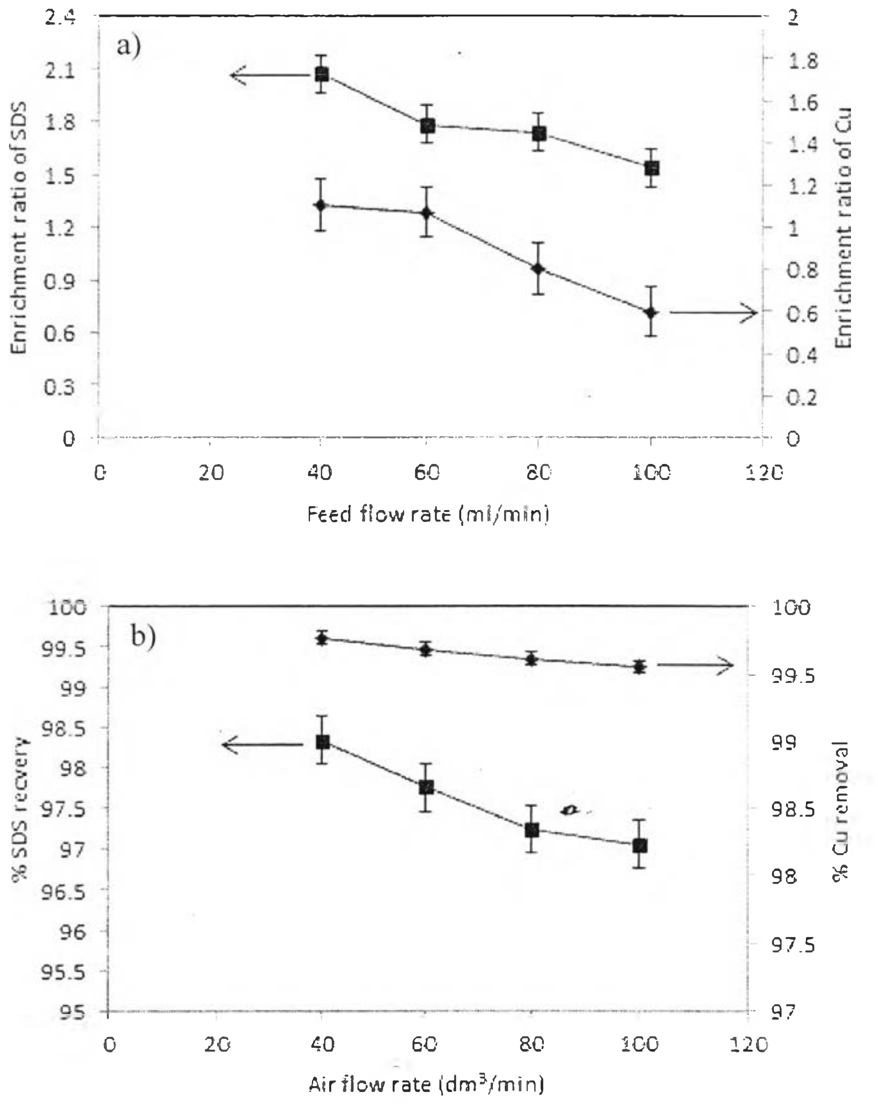


Figure 4.9 Effect of feed flow rate on the enrichment ratios of Cu and SDS (a); SDS recovery and Cu removal (b); and the separation factors of SDS and Cu (c) at foam height = 60 cm, air flow rate = 60 dm^3/min, SDS/Cd = 8/1, feed Cu concentration = 10 mg/L, and number of trays = 5

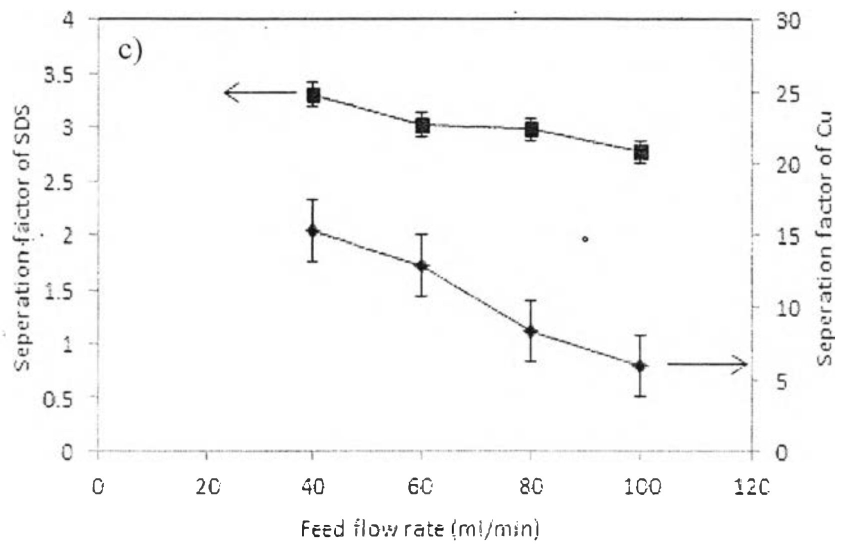


Figure 4.9 Effect of feed flow rate on the enrichment ratios of Cu and SDS (a); SDS recovery and Cu removal (b); and the separation factors of SDS and Cu (c) at foam height = 60 cm, air flow rate = 60 dm^3/min, SDS/Cd = 8/1, feed Cu concentration = 10 mg/L, and number of trays = 5 (con't.)

The Cu removal and SDS recovery can be related to the molar flow rates of Cu and SDS in foamate, respectively, resulting from both adsorptive and bulk liquid transports. The SDS recovery and Cu removal were decreased with increasing feed flow rate, as shown in Figure 4.9b. These results suggest that the increasing bulk liquid transport provides an unequal degree of bulk liquid transport between Cu and SDS, especially at high feed flow rates. The SDS recovery is promoted predominantly by the increase in bulk liquid transport as compared with the Cu removal because the entrained liquid contains predominantly SDS with a very small amount of Cu and most Cu ions adsorb preferentially at the foam surface. In other word, the Cu removal is not promoted by the increasing bulk liquid transport but is mainly governed by the adsorptive transport .

As shown in Figure 4.9c, the separation factors of both SDS and Cu decrease with increasing feed flow rate because the bulk liquid transport has to be minimized in order to achieve maximum separation factors of both SDS and Cu. A feed flow rate of 60 mL/min was selected for further investigation because it was the highest feed flow rate to provide sufficiently high Cu removal.

4.2.3 Removal of Nickel

4.2.3.1 Effect of Molar Ratio

Figure 4.10a shows that an increase in feed SDS/Ni molar ratio increases the Ni removal. This might be attributed to an increase in the adsorptive transport of Ni resulting from both an increase in the ability for foam formation and the increase in the adsorption density of the SDS-Ni complex with increasing feed SDS/Ni molar ratio.

The SDS separation efficiency in terms of recovery showed same trends of Ni. At a feed SDS/Ni ratio (7/1) or more than are slightly increased separation efficiency but at feed molar ratios below 6/1 that could not generated a sufficiently stable foam, as shown in Figures 4.10b. Because the bulk liquid transport is low at feed SDS/Ni molar ratios below 6/1 as mention above, the separation performance of the SDS should be dominantly governed by the adsorptive transport. These results suggest that the adsorptive transport of the SDS does not increase proportionally to the increasing feed molar flow rate of the SDS, although the adsorption density increases with increasing initial SDS concentration.

Figure 4.10c shows that the separation factor of SDS declines sharply with increasing feed SDS/Ni molar ratio at low feed SDS/Ni molar ratios; but it decreases at high feed SDS/Ni molar ratios. This is because of the strong decrease in the enrichment ratio, resulting from the increases in the bulk liquid transport, as indicated by the increase in foamate volumetric ratio. The results can be explained in that the foamate volumetric ratio only slightly increased with increasing feed SDS/Ni molar ratio at low feed SDS/Ni molar ratios but increased significantly at high feed SDS/Ni molar ratios. An optimum feed molar ratio of SDS/Ni should be around 8/1 for the studied ion foam fractionation system.

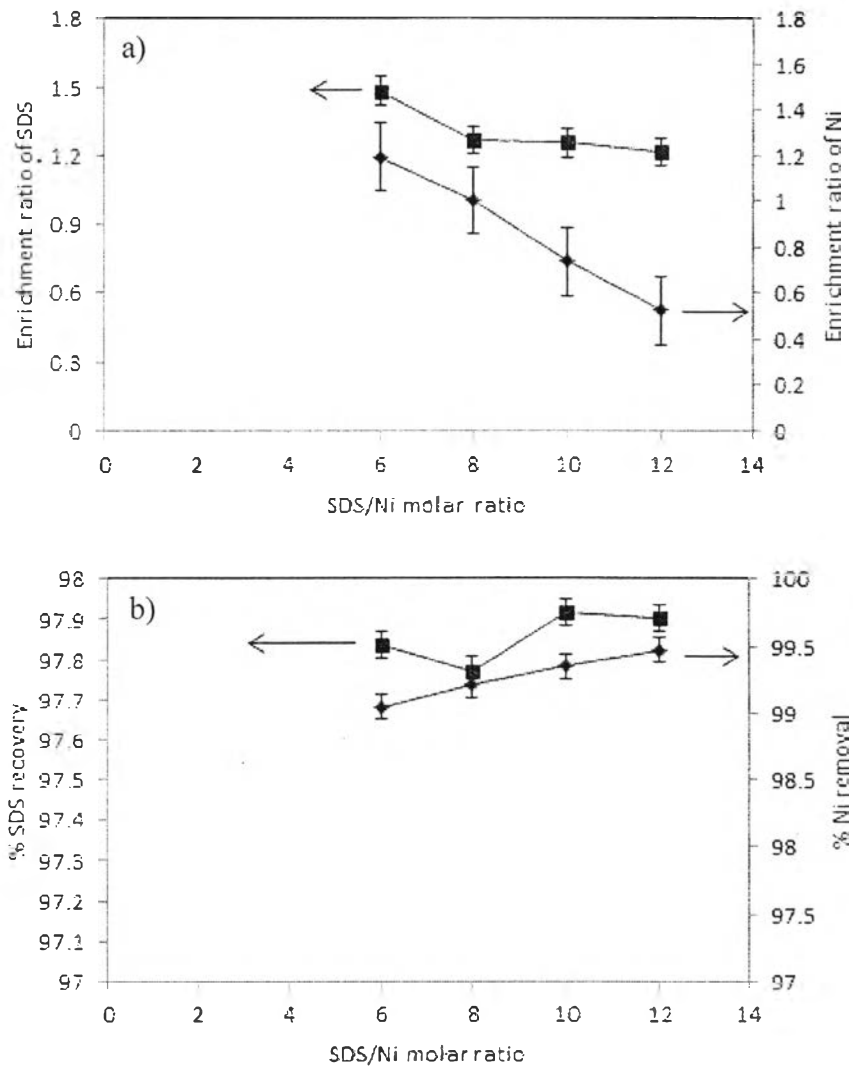


Figure 4.10 Effect of feed SDS/Ni molar ratio on (a) enrichment ratios of SDS and Ni, (b) % SDS recovery and Ni removal, and (c) separation factors of SDS and Ni at an air flow rate of 80 L/min, a feed flow rate of 60 mL/min, a foam height of 60 cm, a feed Ni concentration of 10 mg/L, and the number of trays equal to 5.

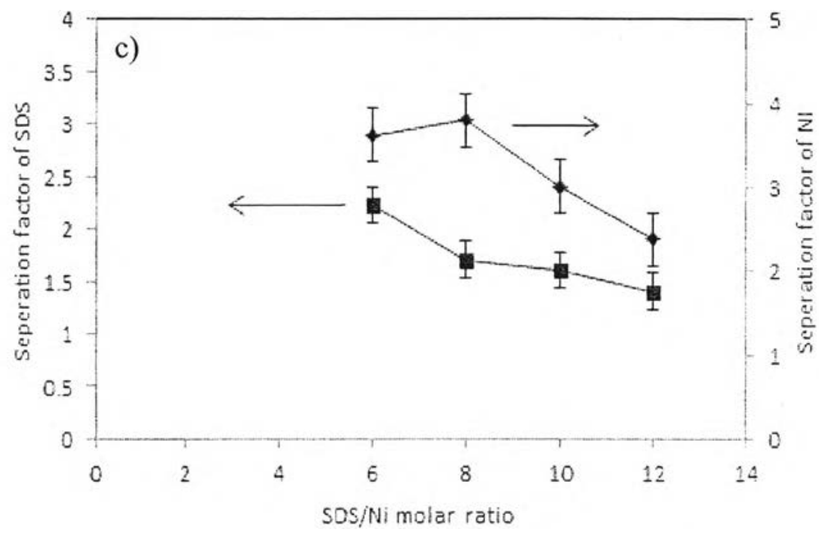


Figure 4.10 Effect of feed SDS/Ni molar ratio on (a) enrichment ratios of SDS and Ni, (b) % SDS recovery and Ni removal, and (c) separation factors of SDS and Ni at an air flow rate of 80 L/min, a feed flow rate of 60 mL/min, a foam height of 60 cm, a feed Ni concentration of 10 mg/L, and the number of trays equal to 5. (con't.)

4.2.3.2 Effect of Foam Height

In this section, an air flow rate of 80 dm^3/min and a feed flow rate of 60 mL/min were selected to run the multistage ion foam fractionation column. A lowest feed SDS/Ni molar ratio of 8/1 was found to be necessary to produce stable foam proficient reaching to reach a foam height of 90 cm.

An increase in foam height results in an enhancement in the enrichment ratios of both SDS and Ni, especially at the highest foam height (90 cm), as shown in Figure 4.11a. This is because the increase in foam height increases the foam residence time, which allows more drainage of the liquid in the foam films, as indicated by the large decrease in foamate volumetric ratio with increasing foam height. This decrease suggests that the bulk liquid transport is reduced with increasing foam height. The effect of feed SDS/Ni molar ratio on the reduction in the enrichment ratios was much more profound at the higher foam height of 90 cm as compared to the lower foam height of 30 cm and 60 cm. The results can be explained by the fact that the foamate volumetric ratio decreased significantly with increasing foam height. This is most likely because Gibbs–Marangoni effects are suppressed at high bulk surfactant concentrations, leading to a very high liquid drainage rates in the produced foam.

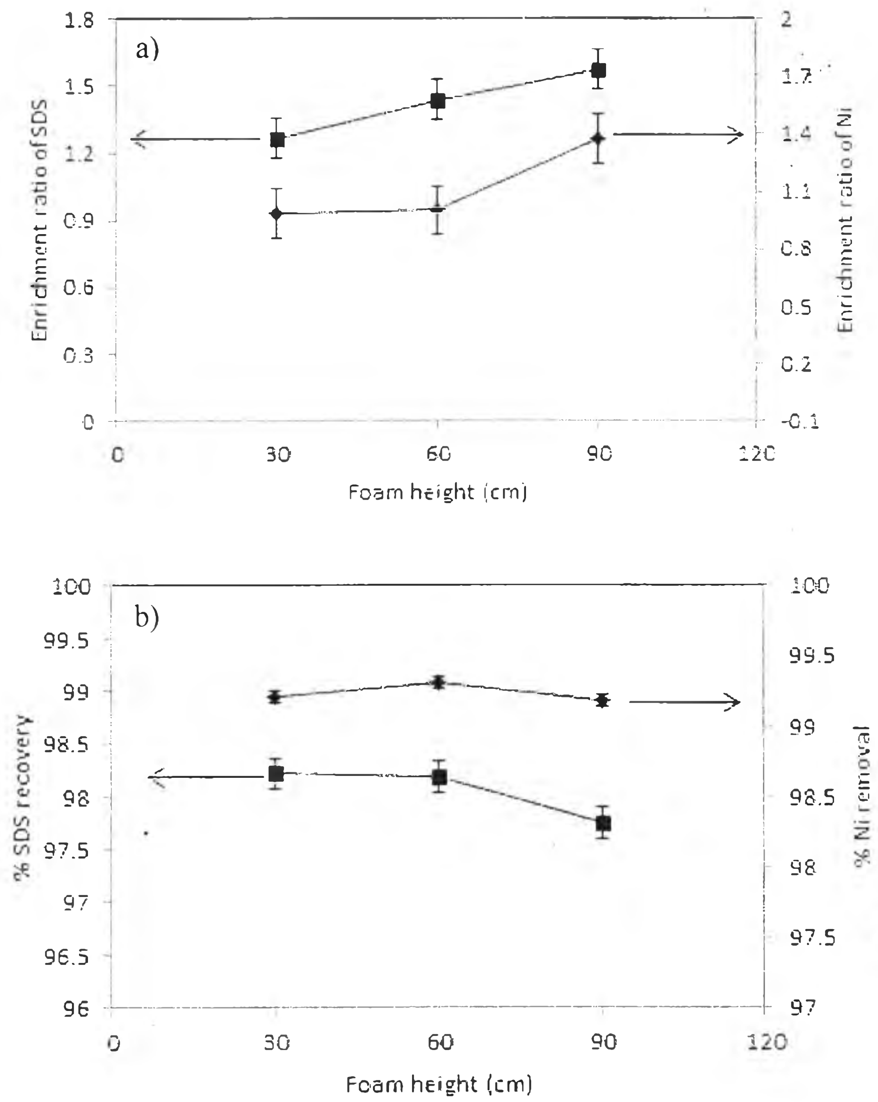


Figure 4.11 Effect of foam height on (a) the enrichment ratios of Ni and SDS; (b) SDS recovery and Ni removal; and (c) the separation factors of SDS and Ni at air flow rate = 80 dm^3/min, feed flow rate = 60 mL/min, number of trays =5, feed Ni concentration = 10 mg/L, and a feed SDS/Ni molar ratios of 8/1.

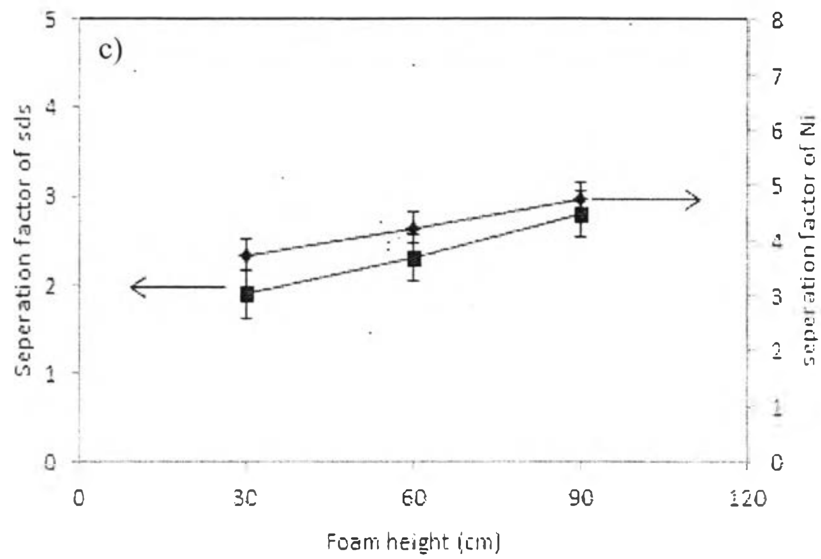


Figure 4.11 Effect of foam height on (a) the enrichment ratios of Ni and SDS; (b) SDS recovery and Ni removal; and (c) the separation factors of SDS and Ni at air flow rate = 80 dm^3/min, feed flow rate = 60 mL/min, number of trays =5, feed Ni concentration = 10 mg/L, and a feed SDS/Ni molar ratios of 8/1. (con't.)

The reduction in SDS recovery was found to be decreased at foam height 60 cm because of the larger decrease in foamate volumetric ratio.

However, the Ni removal almost slightly changed with increasing foam height, as shown in Figures 4.11b. These results expressed that the draining liquid contains a small amount of unadsorbed Ni while most Ni ions co-adsorb with the SDS onto the foam interface. Hence, a reduction of the bulk liquid transport does not decrease the molar flow rate of Ni in the foamate and does not significantly increase the concentration of Ni in the effluent. From the results, it can be concluded that the molar flow rate of Ni in the foamate is governed by adsorptive transport.

Moreover, an increasing foam height, a decrease in the contribution of the bulk liquid transport of SDS to the molar flow rate of SDS in foamate becomes significant. At the lowest foam height of 30 cm, the system generated wet foam, which contains a larger amount of bulk liquid with relatively high SDS concentration and a lower Ni concentration than those of dry foam. At the highest foam height of

90 cm, the foam is extremely dry and the effect of the bulk liquid transport on the molar ratio of SDS/Ni in the foamate is less evident.

Figure 4.11c shows the effects of foam height on the separation factors of SDS and Ni. The separation factors showed to have the same trend as the enrichment ratios for both Ni and SDS. The separation factors of both were enhanced with increasing foam height due to the increase in liquid film drainage (the reduction of bulk liquid transport). The effect of foam height became more prominent as the foam height increased from 60 to 90 cm. These results suggest that the liquid film drainage is an important mechanism for enhancing separation efficiency in a foam fractionation process.

4.2.3.3 Effect of Air Flow Rate

The effect of air flow rate was investigated by varying the air flow rate in the range of 40 to 100 dm^3/min and the other operational parameters were fixed at a feed flow rate of 60 mL/min, a foam height of 60 cm, the number of trays at 5. The lowest feed SDS/Ni molar ratio of 8/1 was used to operate the studied multistage ion foam fractionation unit because it could produce stable foam. The enrichment ratios of both SDS and Ni decrease with increasing air flow rate, as shown in Figure 4.12a. The results can be explained by the fact that the foamate volumetric ratio increased with increasing air flow rate. This increase in foamate volumetric ratio indicates an increase in the bulk liquid transport. As a consequence, the foamate contained more water fraction and less SDS and Ni concentrations, leading to lowering enrichment ratios.

Both SDS recovery and Ni removal were increased with increasing air flow rate for both feed SDS/Ni molar ratios. Because the increase in the adsorptive transport. The increase in Ni removal with increasing air flow rate above 60 dm^3/min, indicating the increase in the bulk liquid transport because increase in volume of foamate. At below 60 dm^3/min, foam could not generate stable foam. However, the increase in SDS recovery with increasing air flow rate is due to both mechanisms. This explanation can be also supported by the fact that the profile of SDS recovery mirrors that of the volumetric ratio, that define is volume of foamate to volume of feed, as shown in Figures 4.12b. The molar ratio of SDS/Ni in the foamate increased with increasing air flow rate and it mirrored the foamate volumetric ratio, suggesting that an increasing air flow rate can increase both adsorptive and bulk liquid transport and, at very high air flow rates, the bulk liquid transport becomes predominantly. However, at an extremely high air flow rate, the system cannot produce stable foam, causing the system to reach a maximum separation performance.

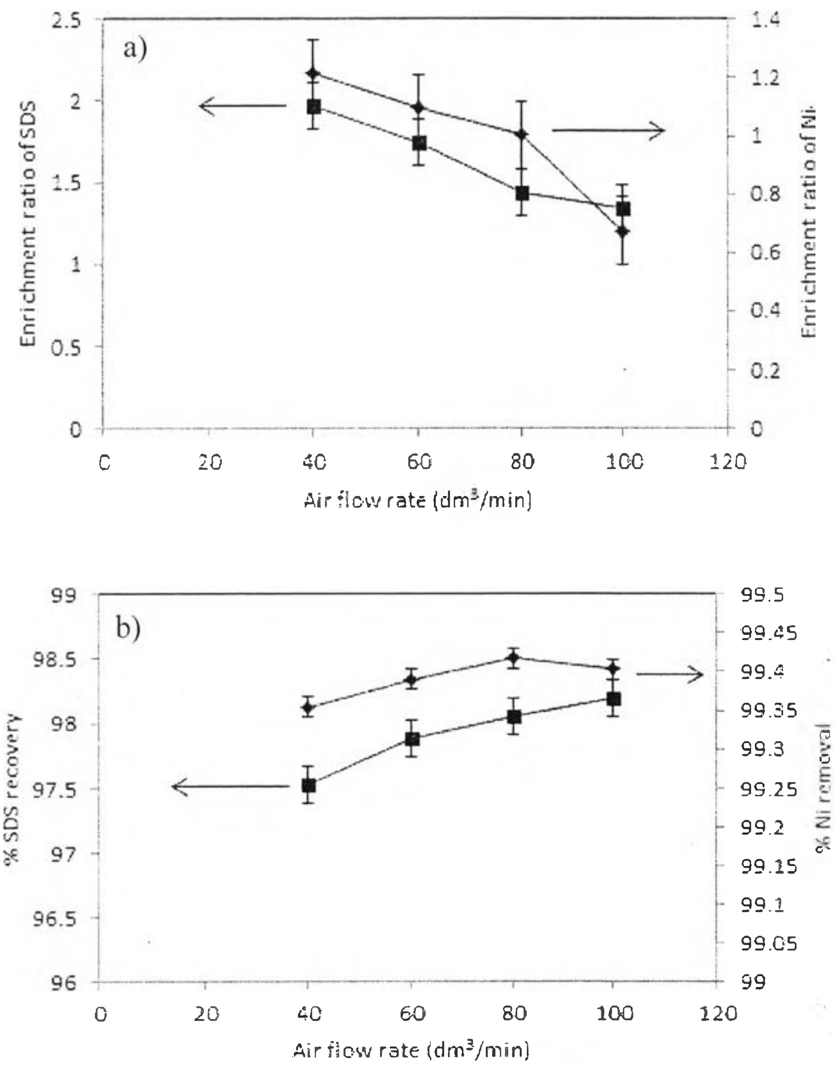


Figure 4.12 Effect of air flow rate on the enrichment ratios of Ni and SDS (a); SDS recovery and Ni removal (b); and the separation factors of SDS and Ni (c) at foam height = 60 cm, feed flow rate = 60 mL/min, number of trays = 5, feed Ni concentration = 10 mg/L, and a feed molar ratios of SDS/Ni of 8/1.

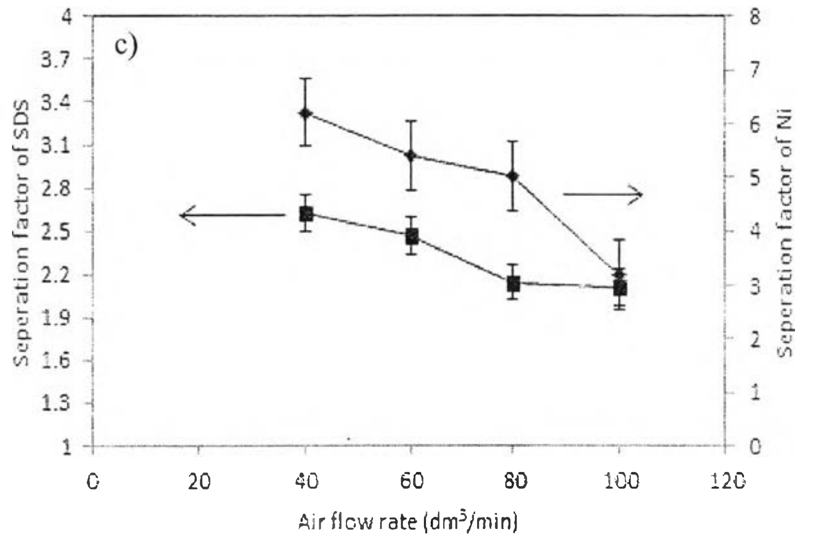


Figure 4.12 Effect of air flow rate on the enrichment ratios of Ni and SDS (a); SDS recovery and Ni removal (b); and the separation factors of SDS and Ni (c) at foam height = 60 cm, feed flow rate = 60 mL/min, number of trays = 5, feed Ni concentration = 10 mg/L, and a feed molar ratios of SDS/Ni of 8/1. (con't.)

Figure 4.12c shows the effect of air flow rate on the separation factors of SDS and Ni. The separation factors of SDS and Ni tended to decrease with increasing air flow rate and reached minimum at high air flow rates. Therefore, focusing on Ni removal, the air flow rate of 80 dm^3/min seems to provide both reasonably high Ni removal with high SDS recovery for this studied feed SDS/Ni molar ratios even though the enrichment ratios and separation factors were low. Hence, this air flow rate of 80 dm^3/min was selected to investigate the effect of feed flow rate.

4.2.3.4 Effect of Feed Flow Rate

The effect of feed flow rate on separation efficiency was investigated by varying the feed flow rate in the range of 40 to 100 dm^3/min, while the other operational parameters were fixed at a feed flow rate of 60 mL/min, a foam height of 60 cm, the number of trays at 5. The lowest feed SDS/Cu molar ratio of 8/1 was used to operate the studied multistage ion foam fractionation unit because it could produce sufficiently stable foam.

In this condition, the enrichment ratios of both SDS and Ni were decreased with increasing feed flow rate. This is because the foamate volumetric ratio decreases slightly with increasing feed flow rate, as shown in Figure 4.13a. As a result, the enrichment ratios of both SDS and Ni did not change with feed flow rate, indicating that the system performance is governed by adsorptive transport.

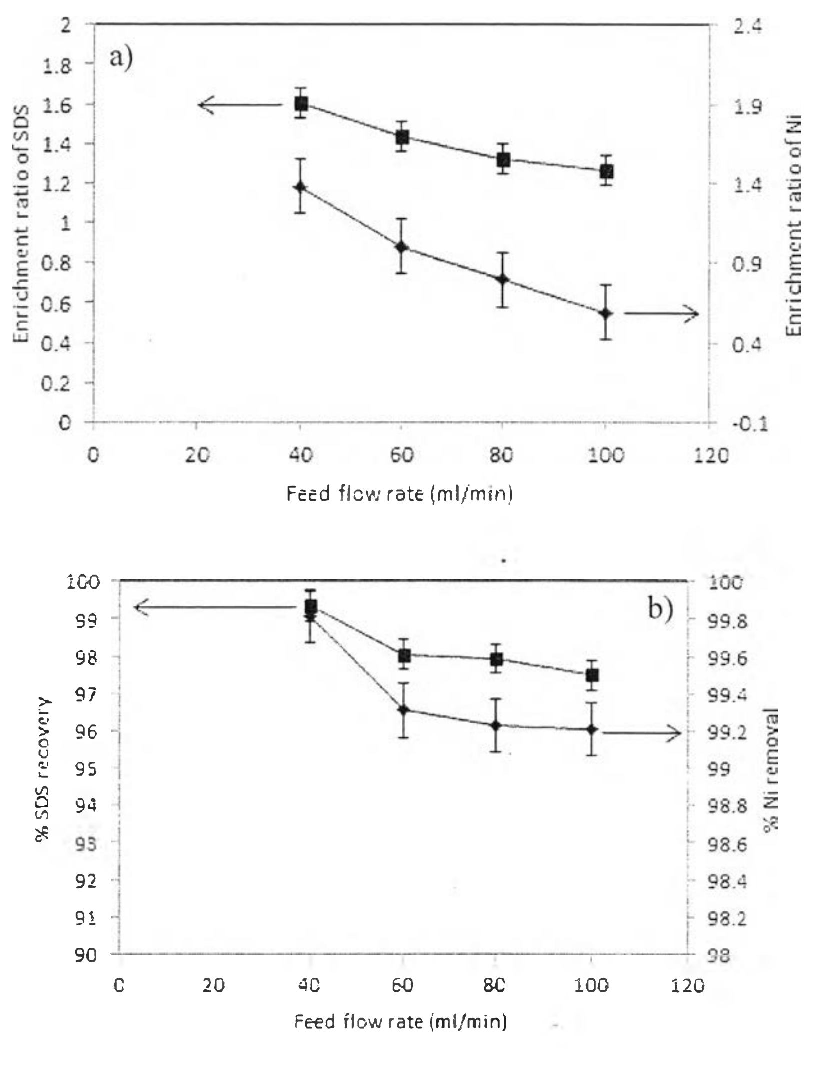


Figure 4.13 Effect of feed flow rate on the enrichment ratios of Ni and SDS (a); SDS recovery and Ni removal (b); and the separation factors of SDS and Ni (c) at foam height = 60 cm, air flow rate = 60 dm^3/min, SDS/Ni = 8/1, feed Ni concentration = 10 mg/L, and number of trays = 5

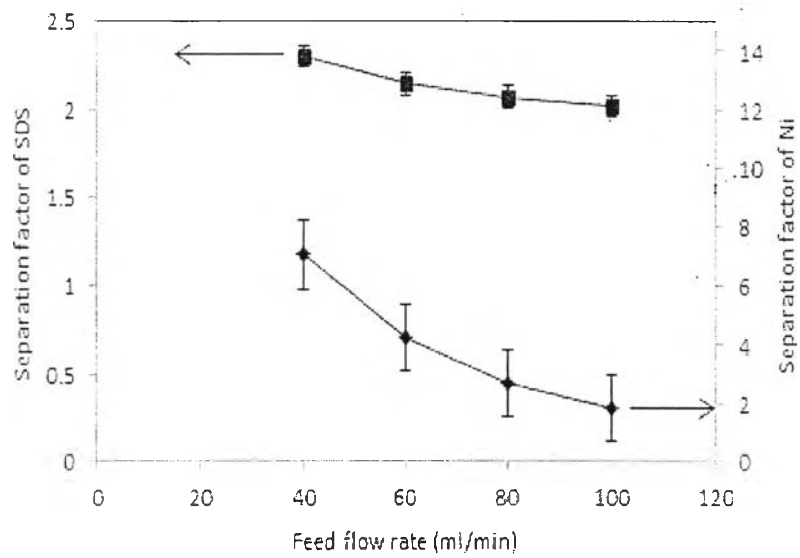


Figure 4.13 Effect of feed flow rate on the enrichment ratios of Ni and SDS (a); SDS recovery and Ni removal (b); and the separation factors of SDS and Ni (c) at foam height = 60 cm, air flow rate = 60 dm^3/min, SDS/Ni = 8/1, feed Ni concentration = 10 mg/L, and number of trays = 5 (con't.)

The Ni removal and SDS recovery can be related to the molar flow rates of Ni and SDS in foamate, respectively, resulting from both adsorptive and bulk liquid transports. The SDS recovery and Ni removal were decreased with increasing feed flow rate, as shown in Figure 4.13b. These results suggest that the increasing bulk liquid transport provides an unequal degree of bulk liquid transport between NI and SDS, especially at high feed flow rates. The SDS recovery is promoted predominantly by the increase in bulk liquid transport as compared with the Ni removal because the entrained liquid contains predominantly SDS with a very small amount of Ni and most Ni ions adsorb preferentially at the foam surface. In other word, the Ni removal is not promoted by the increasing bulk liquid transport but is mainly governed by the adsorptive transport.

As shown in Figure 4.13c, the separation factors of both SDS and Ni decrease markedly with increasing feed flow rate because the bulk liquid transport has to be minimized in order to achieve maximum separation factors of both SDS and Ni. A feed flow rate of 60 mL/min was selected for further investigation because it was the highest feed flow rate to provide sufficiently high Ni removal.

4.3 Removal of Mixed Heavy Metals

4.3.1 Effect of Molar Ratio

In a foam fractionation operation, it is necessary that both the enrichment ratios and the removals of SDS and heavy metals are possible. An increase in surfactant concentration results in increasing removal but wet foam can be undesirably produced, resulting in lowing enrichment ratios. In previous works, removal individual heavy metal, were selected the optimum condition for removal mixed heavy metals. Hence, an air flow rate of 80 dm^3/min and a feed flow rate of 60 mL/min and foam height 60 cm were selected to run the multistage ion foam fractionation column in order to observe the effect of foam height on separation efficiency. A lowest feed SDS/Cd molar ratio of 8/1 was found to be necessary to produce stable foam. Figure 4.14a shows that an increase in feed SDS/ heavy metal molar ratio increases the heavy metals removal at a feed SDS/ heavy metal ratio of 8/1. At heavy metal ratio of 6/1 was high enrichment ratio because increasing bulk liquid transport and the heavy metal ions preferentially adsorb at the air-water interface of foam, leading to the small amount of unadsorbed heavy metals in the foam lamellae. The SDS separation efficiency in terms of recovery showed same trends of heavy metals. At below a feed SDS/heavy metal ratio (6/1) that could not generated a sufficiently stable foam to pass through the bubble caps of the upper tray due to the very low SDS concentration in the solution, as shown in Figure 4.14b. Because the bulk liquid transport is low at feed SDS/heavy metals molar ratios below 6/1 as mention above, the separation performance of the SDS should be dominantly governed by the adsorptive transport. These results suggest that the adsorptive transport of the SDS does not increase proportionally to the increasing feed molar flow rate of the SDS, although the adsorption density increases with increasing initial SDS concentration.

Figure 4.14c shows that the separation factor of SDS declines sharply with increasing feed SDS/heavy metals molar ratio at low feed SDS/heavy metal molar ratios; but it decreases at high feed SDS/heavy metal molar ratios. This is because of the strong decrease in the enrichment ratio, resulting from the increases in the bulk liquid transport, as indicated by the increase in foamate volumetric ratio. Beyond this optimum feed molar ratio for the SDS/heavy metal, the separation factor of heavy metals slightly decreased with increasing feed SDS/heavy metals molar ratio. The results can be explained in that the foamate volumetric only slightly increased with increasing feed SDS/havy metal molar ratio at low feed SDS/heavy metal molar ratios but increased significantly at high feed SDS/heavy metal molar ratios. By trading off very low heavy metals and reasonably low SDS concentrations in the effluent, an optimum feed molar ratio of SDS/heavy metal should be around 8/1 for the studied ion foam fractionation system.

Figure 4.14d shows the molar ratio of the SDS/Cd in the effluent increases with increasing feed SDS/heavy metal molar ratio. This is because an increase in the feed SDS/ heavy metal molar ratio simply increases the SDS concentration in the system. The results of the molar ratio of SDS/ heavy metal in the effluent and the effluent heavy metal concentration suggest that the effluent heavy metal concentration decreased with increasing the feed SDS/heavy metal molar ratio up to 6/1. Hence, an increase in the feed molar ratio of SDS/heavy metal beyond 7/1 is useless, causing increasing effluent SDS concentration. It is worth mentioning that a high feed SDS/heavy metal molar ratio of 8/1 is necessary to obtain the saturated surface excess concentration (Γ_m) of the SDS-Cd complex and to lower the surface tension.

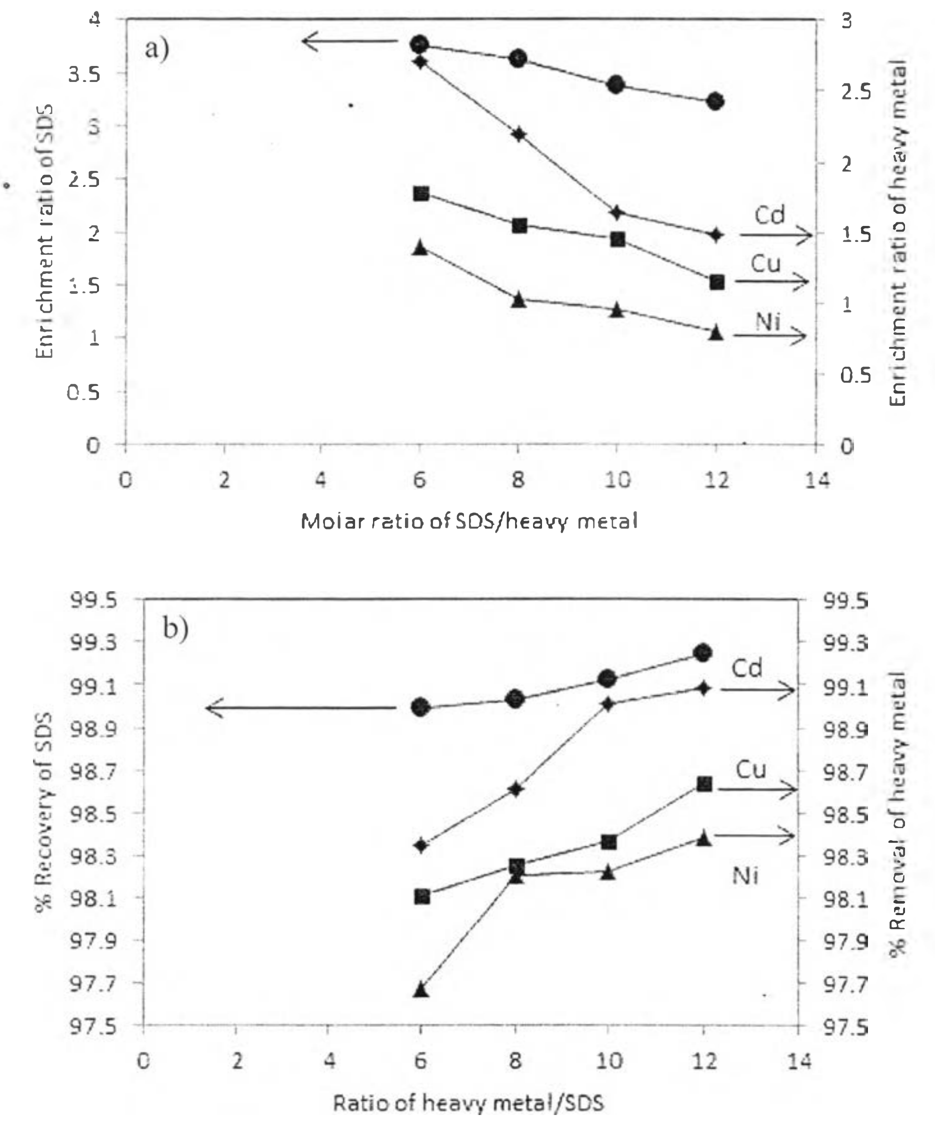


Figure 4.14 Effect of feed SDS/heavy metal molar ratio on (a) enrichment ratios of SDS and heavy metals, (b) % SDS recovery and heavy metals removal, (c) separation factors of SDS and heavy metals, and (d) Effluent concentration of SDS and heavy metals at an air flow rate of 80 L/min, a feed flow rate of 60 mL/min, a foam height of 60 cm, a feed mixed heavy metals concentration of 10 mg/L, and the number of trays equal to 5.

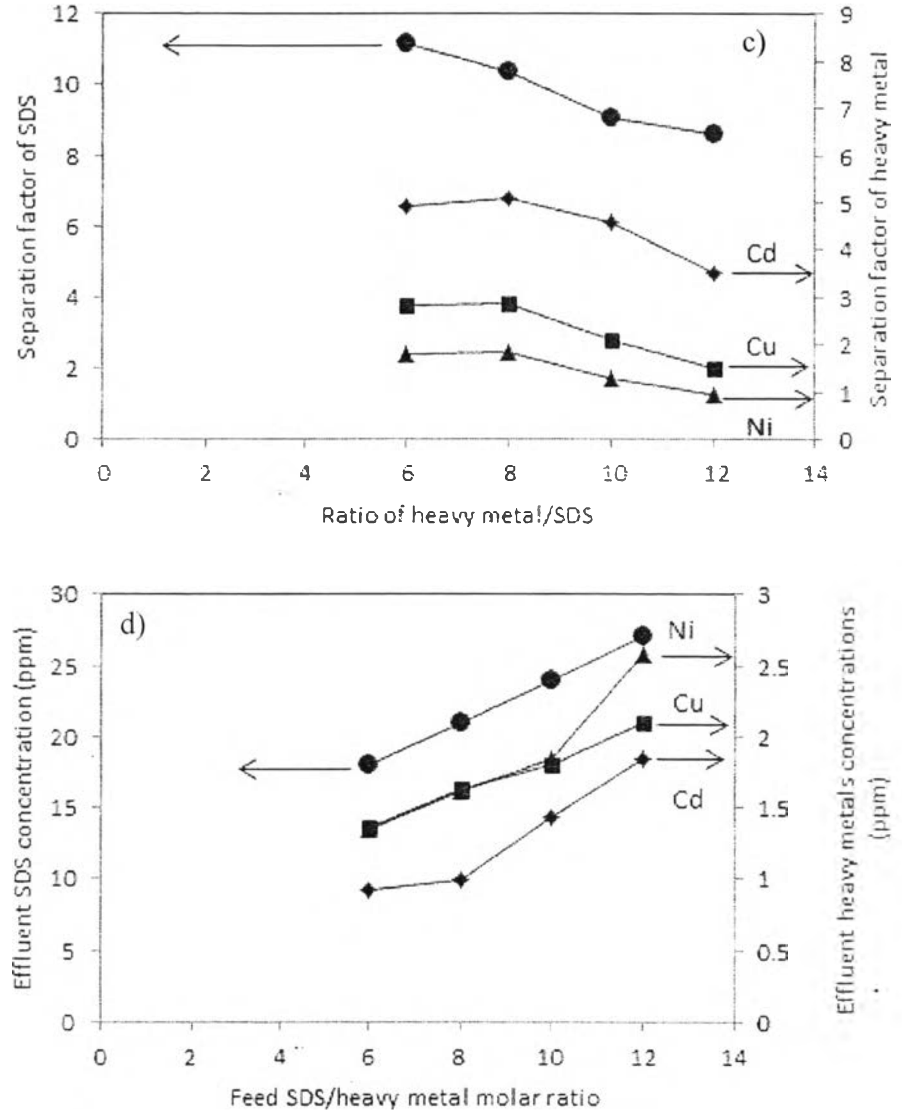


Figure 4.14 Effect of feed SDS/heavy metal molar ratio on (a) enrichment ratios of SDS and heavy metals, (b) % SDS recovery and heavy metals removal, (c) separation factors of SDS and heavy metals, and (d) Effluent concentration of SDS and heavy metals at an air flow rate of 80 L/min, a feed flow rate of 60 mL/min, a foam height of 60 cm, a feed mixed heavy metals concentration of 10 mg/L, and the number of trays equal to 5. (con't.)

4.3.2 Effect of Foam Height

In this section, an air flow rate of 80 dm^3/min and a feed flow rate of 60 mL/min were selected to run the multistage ion foam fractionation column. A lowest feed SDS/ heavy metal molar ratio of 8/1 was found to be necessary to produce stable foam proficient reaching to reach a foam height of 90 cm.

An increase in foam height results in an enhancement in the enrichment ratios of both SDS and heavy metals, especially at the highest foam height (90 cm), as shown in Figure 4.15a. This is because the increase in foam height increases the foam residence time, which allows more drainage of the liquid in the foam films, as indicated by the large decrease in foamate volumetric with increasing foam height. This decrease suggests that the bulk liquid transport is reduced with increasing foam height. The effect of feed SDS/ heavy metal molar ratio on the reduction in the enrichment ratios was much more profound at the higher foam height of 90 cm as compared to the lower foam height of 30 cm and 60 cm. The results can be explained by the fact that the foamate volumetric ratio decreased significantly with increasing foam height. This is most likely because Gibbs–Marangoni effects are suppressed at high bulk surfactant concentrations, leading to a very high liquid drainage rates in the produced foam.

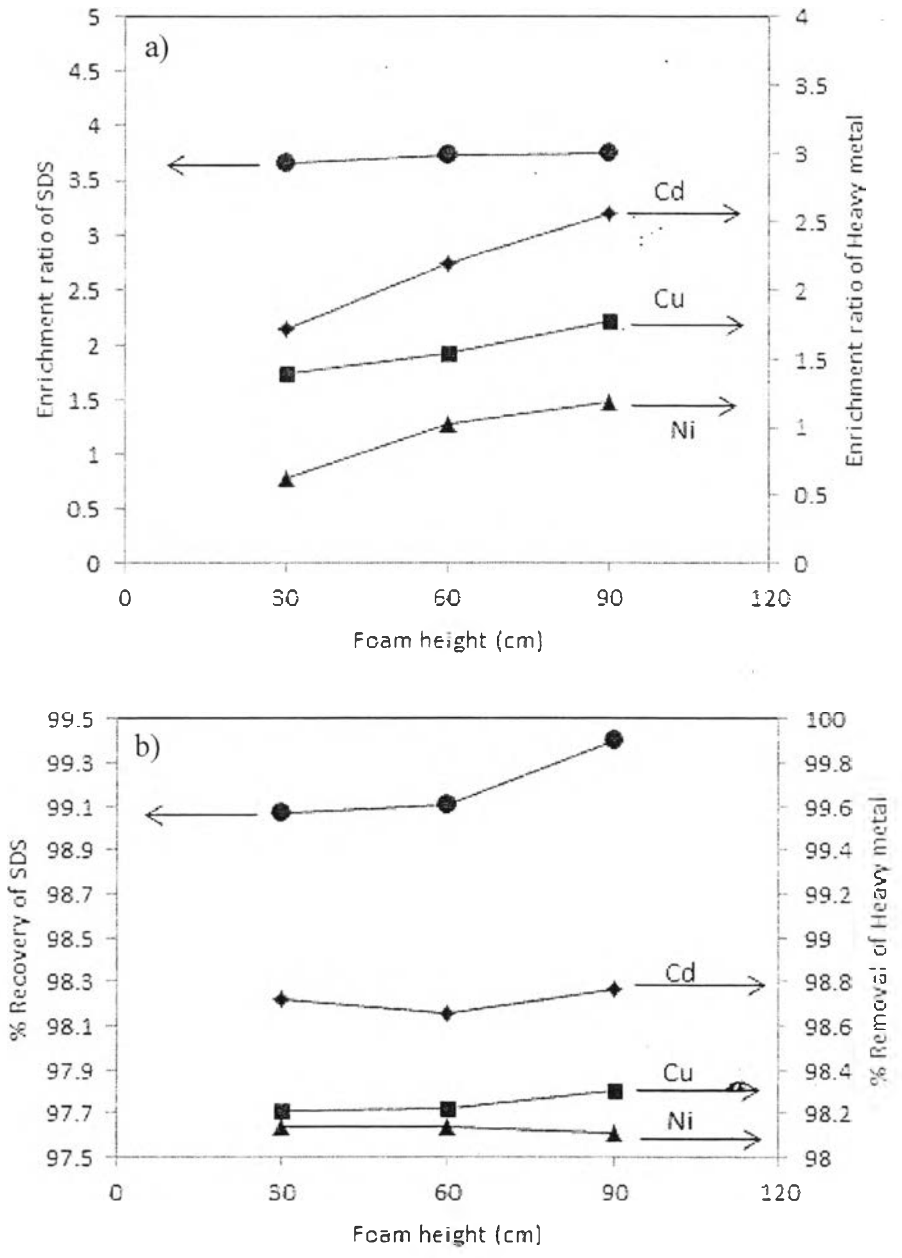


Figure 4.15 Effect of foam height on (a) the enrichment ratios of heavy metals and SDS; (b) SDS recovery and heavy metals removal; (c) the separation factors of SDS and heavy metals; and (d) Effluent concentration of SDS and heavy metals at an air flow rate of 80 L/min, a feed flow rate of 60 mL/min, a foam height of 60 cm, a feed mixed heavy metals concentration of 10 mg/L, and the number of trays equal to 5.

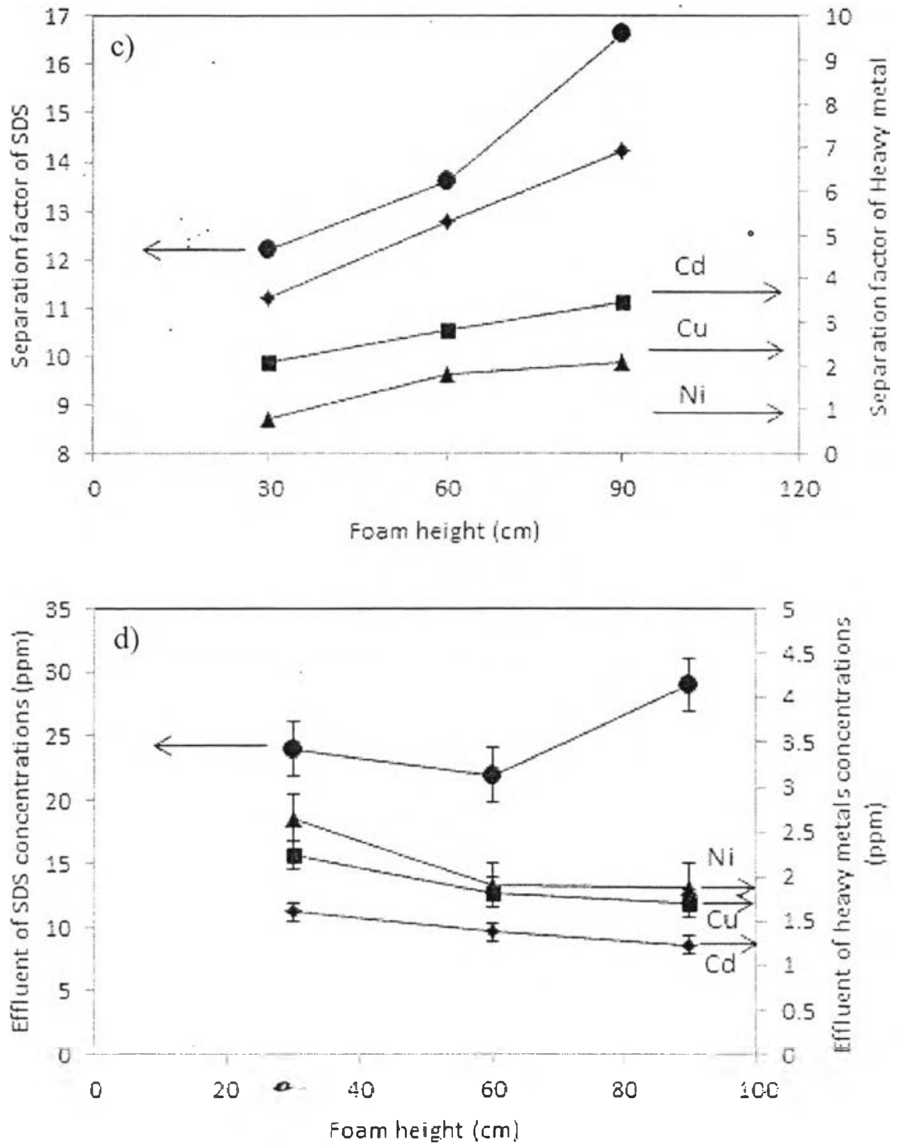


Figure 4.15 Effect of foam height on (a) the enrichment ratios of heavy metals and SDS; (b) SDS recovery and heavy metals removal; (c) the separation factors of SDS and heavy metals; and (d) Effluent concentration of SDS and heavy metals at an air flow rate of 80 L/min, a feed flow rate of 60 mL/min, a foam height of 60 cm, a feed mixed heavy metals concentration of 10 mg/L, and the number of trays equal to 5. (con't.)

However, the mixed heavy metals removal almost slightly changed with increasing foam height, as shown in Figures 4.15b. These results expressed that the draining liquid contains a small amount of unadsorbed Ni while most heavy metal ions co-adsorb with the SDS onto the foam interface. Hence, a reduction of the bulk liquid transport does not decrease the molar flow rate of heavy metals in the foamate and does not significantly increase the concentration of heavy metals in the effluent. From the results, it can be concluded that the molar flow rate of heavy metals in the foamate is governed by adsorptive transport.

Moreover, an increasing foam height, a decrease in the contribution of the bulk liquid transport of SDS to the molar flow rate of SDS in foamate becomes significant. At the lowest foam height of 30 cm, the system generated wet foam, which contains a larger amount of bulk liquid with relatively high SDS concentration and a lower heavy metals concentration than those of dry foam. At the highest foam height of 90 cm, the foam is extremely dry and the effect of the bulk liquid transport on the molar ratio of SDS/ heavy metal in the foamate is less evident. Figure 4.15c shows the effects of foam height on the separation factors of SDS and heavy metals. The separation factors showed to have the same trend as the enrichment ratios for both heavy metals and SDS. The separation factors of both were enhanced with increasing foam height due to the increase in liquid film drainage (the reduction of bulk liquid transport). The effect of foam height became more prominent as the foam height increased from 60 to 90 cm. These results suggest that the liquid film drainage is an important mechanism for enhancing separation efficiency in a foam fractionation process.

Figure 4.15d shows the effect of foam height on both SDS and heavy metal concentrations in the effluent. For both feed SDS/heavy metal molar ratios, the SDS concentration in the effluent increased with increasing foam height. This is because an increase in foam height causes an increase in foam residence time, leading to increasing liquid film drainage. In contrast, the heavy metal concentration in the effluent slightly decreased with increasing foam height. The result can be also explained by the fact that most heavy metal ions co-adsorb with DS^- ions on the air–water interface of the produced foam.

4.3.3 Effect of Air Flow Rate

The effect of air flow rate was investigated by varying the air flow rate in the range of 40 to 100 dm^3/min and the other operational parameters were fixed at a feed flow rate of 60 mL/min, a foam height of 60 cm, the number of trays at 5. The lowest feed SDS/heavy metal molar ratio of 8/1 was used to operate the studied multistage ion foam fractionation unit because it could produce stable foam. The enrichment ratios of both SDS and heavy metals decrease with increasing air flow rate, as shown in Figure 4.16a. The results can be explained by the fact that the foamate volumetric ratio increased with increasing air flow rate. This increase in foamate volumetric ratio indicates an increase in the bulk liquid transport. As a consequence, the foamate contained more water fraction and less SDS and heavy metals concentrations, leading to lowering enrichment ratios.

Figure 4.16b shows that both SDS recovery and heavy metals removal slightly increase with increasing air flow rate for both feed SDS/ heavy metal molar ratios. Because the increase in the adsorptive transport. The small increase in heavy metal removal with increasing air flow rate above 60 dm^3/min, indicating the increase in the bulk liquid transport because increase in volume of foamate. At below 60 dm^3/min, foam could not generate stable foam. However, the increase in SDS recovery with increasing air flow rate is due to both mechanisms. This explanation can be also supported by the fact that the profile of SDS recovery mirrors that of the volumetric ratio, that define is volume of foamate to volume of feed. The molar ratio of SDS/ heavy metal in the foamate increased with increasing air flow rate and it mirrored the foamate volumetric, suggesting that an increasing air flow rate can increase both adsorptive and bulk liquid transport and, at very high air flow rates, the bulk liquid transport becomes predominantly. However, at an extremely high air flow rate, the system cannot produce stable foam, causing the system to reach a maximum separation performance.

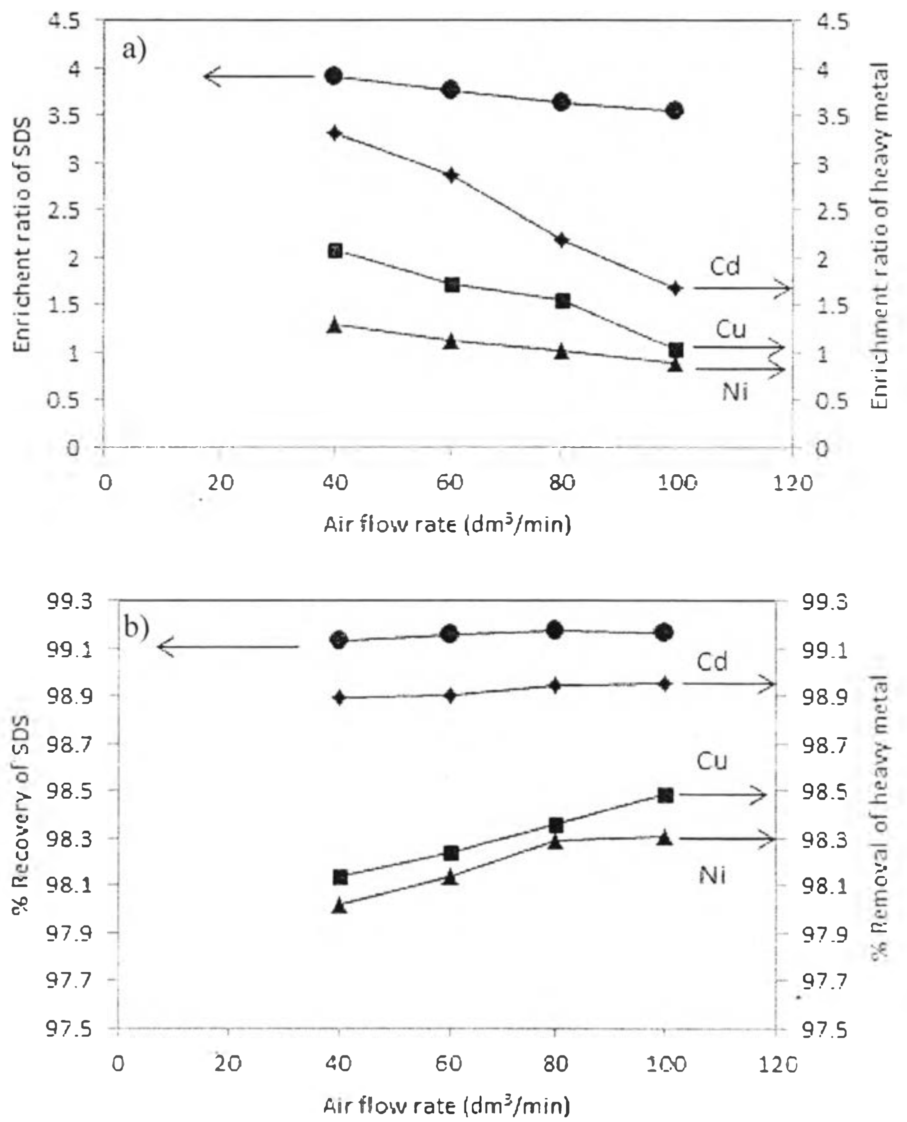


Figure 4.16 Effect of air flow rate on the enrichment ratios of heavy metals and SDS (a); SDS recovery and heavy metals removal (b); and the separation factors of SDS and heavy metals (c) at foam height = 60 cm, feed flow rate = 60 mL/min, number of trays = 5, feed Ni concentration = 10 mg/L, and a feed molar ratios of SDS/Ni of 8/1.

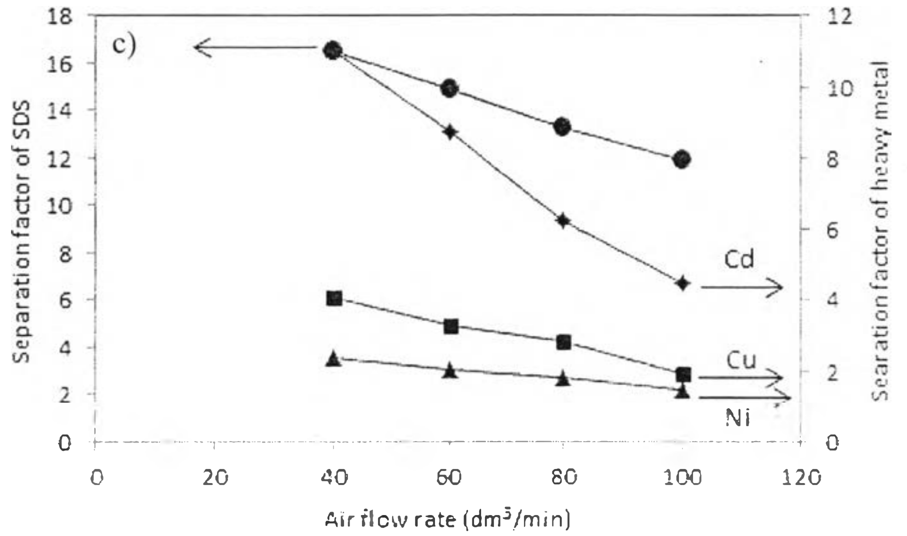


Figure 4.16 Effect of air flow rate on the enrichment ratios of heavy metals and SDS (a); SDS recovery and heavy metals removal (b); and the separation factors of SDS and heavy metals (c) at foam height = 60 cm, feed flow rate = 60 mL/min, number of trays = 5, feed Ni concentration = 10 mg/L, and a feed molar ratios of SDS/Ni of 8/1. (con't.)

Figure 4.12c shows the effect of air flow rate on the separation factors of SDS and heavy metals. The separation factors of SDS and heavy metals tended to decrease with increasing air flow rate and reached minimum at high air flow rates. Therefore, focusing on heavy metals removal, the air flow rate of 80 dm^3/min seems to provide both reasonably high heavy metals removal with high SDS recovery for this studied feed SDS/ heavy metal molar ratios even though the enrichment ratios and separation factors were low. Hence, this air flow rate of 80 dm^3/min was selected to investigate the effect of feed flow rate. In this case of mixed heavy metals, Cd is separated more than Cu and Ni because the larger ions are preferentially adsorbed because their outer secondary hydration water molecules are more easily to be lost when interacting with the anionic surfactant adsorbed at the interface.

4.3.4 Effect of Feed Flow Rate

The effect of feed flow rate on separation efficiency was investigated by varying the feed flow rate in the range of 40 to 100 dm^3/min, while the other operational parameters were fixed at a feed flow rate of 60 mL/min, a foam height of 60 cm, the number of trays at 5. The lowest feed SDS/Cu molar ratio of 8/1 was used to operate the studied multistage ion foam fractionation unit because it could produce sufficiently stable foam.

In this condition, the enrichment ratios of both SDS and heavy metals changed slightly with increasing feed flow rate. This is because the foamate volumetric ratio decreases slightly with increasing feed flow rate, as shown in Figure 4.17a. As a result, the enrichment ratios of both SDS and heavy metals did not change with feed flow rate, indicating that the system performance is governed by adsorptive transport.

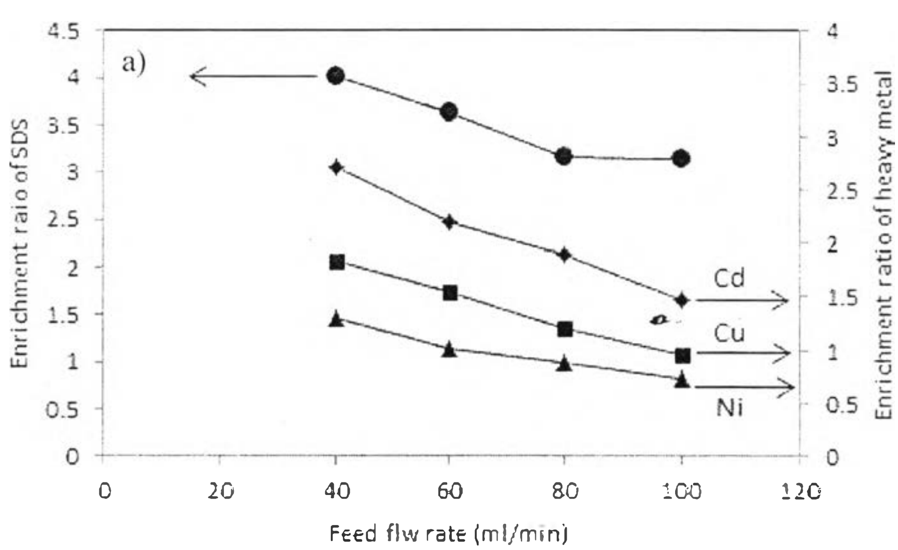


Figure 4.17 Effect of feed flow rate on the enrichment ratios of heavy metals and SDS (a); SDS recovery and heavy metals removal (b); and the separation factors of SDS and heavy metals (c) at foam height = 60 cm, air flow rate = 60 dm^3/min, SDS/Ni = 8/1, feed Ni concentration = 10 mg/L, and number of trays = 5

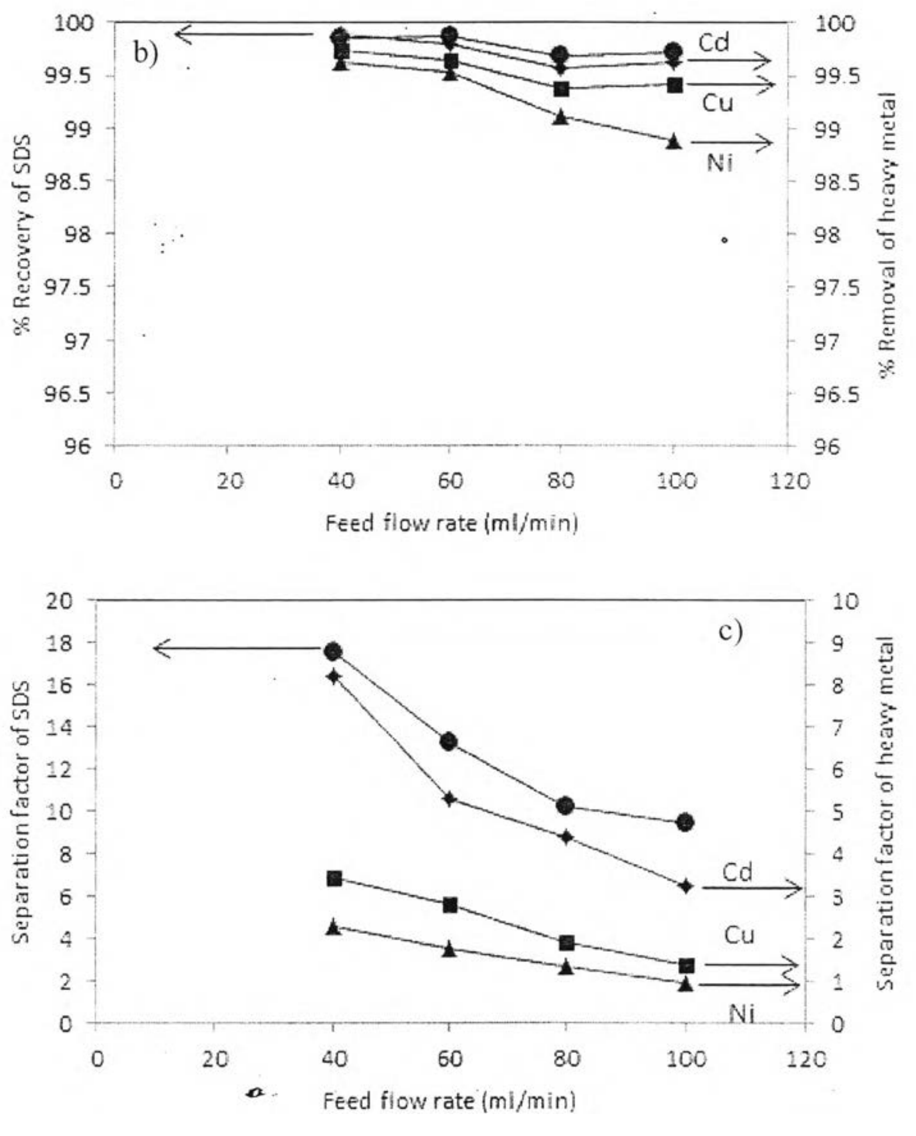


Figure 4.17 Effect of feed flow rate on the enrichment ratios of heavy metals and SDS (a); SDS recovery and heavy metals removal (b); and the separation factors of SDS and heavy metals (c) at foam height = 60 cm, air flow rate = 60 dm^3/min, SDS/Ni = 8/1; feed Ni concentration = 10 mg/L, and number of trays = 5 (con't.)

The heavy metals removal and SDS recovery can be related to the molar flow rates of heavy metals and SDS in foamate, respectively, resulting from both adsorptive and bulk liquid transports. The SDS recovery and heavy metals removal decreased with increasing feed flow rate, as shown in Figure 4.17b. These results suggest that the increasing bulk liquid transport provides an unequal degree of bulk liquid transport between heavy metals and SDS, especially at high feed flow rates. The SDS recovery is promoted predominantly by the increase in bulk liquid transport as compared with the heavy metals removal because the entrained liquid contains predominantly SDS with a very small amount of heavy metals and most heavy metals ions adsorb preferentially at the foam surface. In other word, the heavy metals removal is not promoted by the increasing bulk liquid transport but is mainly governed by the adsorptive transport.

Figure 4.17c shows that the separation factors of both SDS and heavy metals decrease markedly with increasing feed flow rate because the bulk liquid transport has to be minimized in order to achieve maximum separation factors of both SDS and heavy metals. A feed flow rate of 60 mL/min was selected for further investigation because it was the highest feed flow rate to provide sufficiently high heavy metals removal.

4.4 Competitive Removal of Mixed Heavy Metals

In this case of mixed heavy metals, Cd is separated more than Cu and Ni because the larger ions are preferentially adsorbed because their outer secondary hydration water molecules are more easily to be lost when interacting with the anionic surfactant adsorbed at the interface, as shown in Figure 4.18.

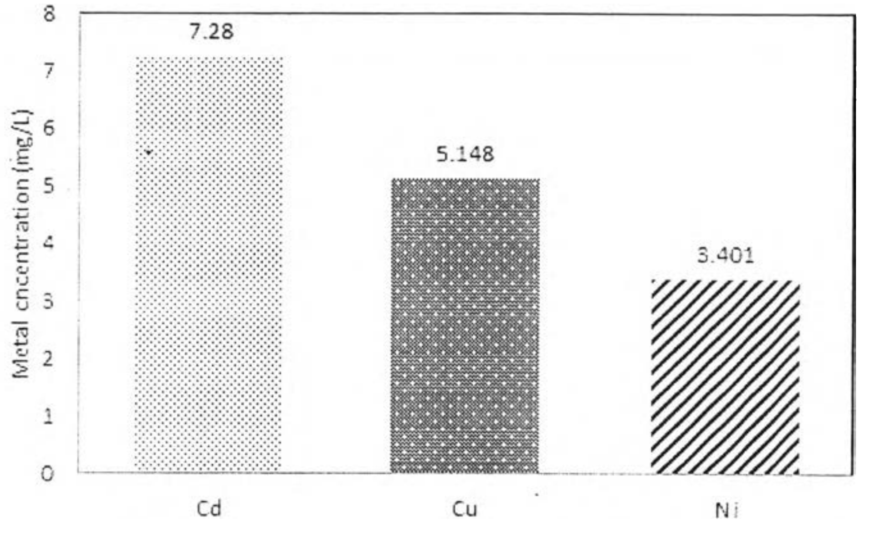


Figure 4.18 Heavy metal concentrations at foam height = 60 cm, air flow rate = 60 dm^3/min, SDS/Ni = 8/1, feed Ni concentration = 10 mg/L, and number of trays = 5