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Article

# Protein Removal by a Foam Fractionator in Simulated Seawater Aquaculture System

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**Abstract :** Effects of different operating factors including superficial air velocity (SAV), hydraulic residence time (HRT), protein concentration, and foam overflow height on protein removal by a foam fractionator in simulated seawater aquaculture system were investigated. This experiment was conducted on batch and consecutive modes at different combinations of the affecting factors. The foam fractionator had a diameter of 20 cm and a height of 120 cm and the experiment was conducted with synthetic wastewater. In 5 consecutive trials, protein concentrations in culture tank water decreased faster when the foam fractionator was operated at higher SAVs and lower HRTs. In batch trials, protein removal rates increased with an increase in SAV but decreased with an increase in HRT. Higher protein concentrations in the bulk solution resulted in higher protein removal rates. Protein concentrations in the collected foam condensates increased but the foam overflow rates decreased with the increase of foam overflow heights. The results of this experiment indicate that foam fractionation would be an effective way for protein removal in seawater aquaculture systems and the performance of the foam fractionator depends largely on the operating parameters, especially SAV.

**Key words :** protein removal, foam fractionator, superficial air velocity, HRT, foam condensate

## 1. Introduction

Foam fractionation is one of the foam separation methods that involve separation of solutes as well as particulates by their preferential attachment to rising air bubbles (Rubin 1981). The key element in this process is surfactant. Foam fractionation has also been used successfully to separate surface-active materials such as enzymes and other proteins (Charm 1972) and has already been considered a treatment process in recirculating aquaculture systems (Dwivedy 1973; Wheaton 1977; Huguenin and Colt 1989; Spotte 1992). Although fatty acids could be possible candidate for surfactants, Chen *et al.* (1993a) measured relatively low fatty acid concentrations in foam condensates when compared with protein concentrations and they concluded that fatty acids are negligible. In aquaculture systems, protein is usually considered the main surfactant since protein is a major component of fish feed, usually constituting from 30 to 50 percent of the formulated feed (Downey 1981), and protein leached from uneaten feed and fish feces or directly excreted by fish should be substantial.

Concentration of protein in aquaculture systems is affected not only by the feed supplied and the fish species cultured, but also, to a large extent, by the culture system. Chen *et al.* (1993a) analyzed protein and total suspended solid (TSS) concentrations in culture waters from three different culture systems and found great differences between them. Up to 127 mg/*l* of protein was found in the system with a low water exchange rate. Decomposition of these proteins would contribute to high ammonia concentrations in aquaculture systems, so proteins contained in volatile solids, along with dissolved proteins, should be removed from the aquaculture system. Foam fractionation

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is preferred for this purpose due to the low construction cost, low energy consumption, easy management, and easy adaptation to almost any kind of recirculating aquaculture system.

Lomax (1976) found that, in terms of cost and effectiveness, biofilters with foam fractionation was the best design combination after examination of several fish culture systems. Dwivedy (1973) found that foam fractionators removed solids and helped to maintain pH in an oyster culture system. Besides, foam fractionator can serve as a gas-stripping unit, which is usually a necessary treatment process in recirculating aquaculture systems for assuring fish survival and growth (Chen *et al.* 1993b). Others reported that foam fractionation can be used to remove fine solids and excessive nutrients (Chen 1991; Weeks *et al.* 1992; Chen *et al.* 1993c; Chen *et al.* 1994a, b).

Many studies have been done on protein removal by foam fractionation. Chen *et al.* (1993a) determined that only 11% of the proteins could act as a surfactant and be removed from the aquaculture water and they modeled protein removal in freshwater systems (Chen *et al.* 1994a, b). Suh and Lee (1995) and Suh *et al.* (2002) also found a partial protein removal by a foam fractionator in a tilapia culture system. Lomax (1976) confirmed solids removal by foam fractionator and recommended that the substances responsible for foam fractionation should be identified. However, all these experiments were done in freshwater systems. Recently, Suh *et al.* (2000a) investigated protein removal characteristics in seawater systems using synthetic wastewater, which was made by mixing collected foam condensate with seawater, but without giving the detailed operating parameters. Suh *et al.* (1999) modeled the protein removal by foam fractionation in a seawater system using egg white as a protein source. However, protein concentrations used in their experiments were higher than commonly reported in aquaculture system (Chen *et al.* 1993a). Also, the use of egg white instead of natural proteins produced in an aquaculture system makes direct application of their findings questionable. Huguenin and Colt (1989) already pointed out the lack of the actual performance data and the need to identify and quantify the organic components involved in the foam fractionation process.

Spotte (1979) has stated that the main factors affecting the efficiency of foam fractionation include HRT, bubble size, airflow rate, diffuser submergence depth, foam overflow height, and the configuration of the foam fractionator itself. For an existed foam fractionator, the factors affecting foam fractionation include airflow rate, water flow rate, and foam overflow height (Weeks *et al.* 1992).

Here in this experiment, protein removal efficiencies of an air drift foam fractionator were evaluated at different foam overflow heights, SAVs, and HRTs in a simulated seawater recirculating aquaculture system. Synthetic wastewater was obtained by mixing waste collected from a freshwater recirculating aquaculture system with artificial seawater. Protein and solid contents of the synthetic wastewater were within the ranges usually reported in recirculating aquaculture systems. The obtained data would be helpful for selecting operational parameters in applying foam fractionation in seawater aquaculture systems.

## 2. Materials and methods

### System configuration and experimental procedure

The experiment system consisted of a round, 300-L plastic culture tank, a recirculating pump, a foam fractionator, an air distribution system, and foam collection facilities (Fig. 1). Synthetic wastewater was pumped from the culture tank into the foam fractionator and then back to the culture tank or was wasted according to the different set of trials. A bypass was connected to the main outflow from the pump for adjusting the water flow rate to the foam fractionator.

In order to obtain equal solid and protein concentrations in culture tank water for each set of trials, sediments from the first sedimentation basin of a recirculating system in Pukyong National University were collected and mixed with an electric stirrer, and then equal aliquots were stored in a frozen state in a refrigerator. The sedimentation basin was cleaned once a day, so the collected sediments were kept relatively fresh. They should consist mainly of feces

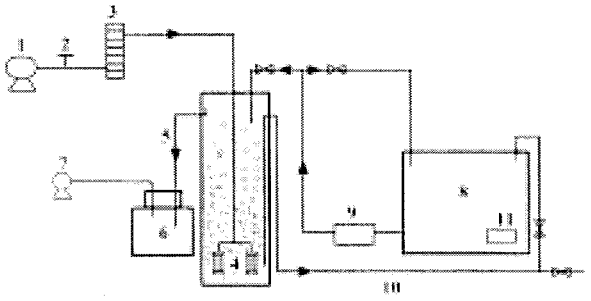

**Fig. 1. Schematic diagram of foam fractionation system. 1, air blower; 2, pressure regulator; 3, airflow meter; 4, air diffuser; 5, foam collection pipe; 6, foam collection bottle; 7, vacuum pump; 8, culture tank; 9, recirculating pump; 10, outflow line; 11, mixing pump.**

and uneaten feed, which are the main solid wastes in the fish culture system. Foam condensates produced in the same recirculating aquaculture system were also collected and stored as was the case for sediments. Foam condensate and sediments were mixed together to form the synthetic wastewater. All the tests were conducted at a water temperature of 20°C and pH values were within the range of 7.8-7.9.

Protein removal rates were evaluated at 4 different airflow rates of 7, 14, 21, and 28 *l*/min, 5 HRTs of 1, 2, 3, 4, and 6 min, and 4 foam overflow heights of 1, 3, 5, and 7 cm. Superficial air velocity, which is defined as the ratio of volumetric airflow through the fractionator column and the cross sectional area of the column, was used instead of the airflow rate since it is a convenient way of expressing airflow velocity through a foam fractionator column and the corresponding SAV values were 0.371, 0.743, 1.114, and 1.486 cm/sec, respectively.

In the first set of trials, selected combinations of operating parameters were tested and trials were conducted on a batch mode. Protein removal rates were tested at different initial protein concentrations. Removal rates were calculated according to Suh *et al.* (2000b).

$$-r_a = \frac{C_{i,a} \times Q_i - C_{o,a} \times Q_i}{V}$$

Where, $-r_a$, removal rate (g/*l* · day); $C_{i,a}$, protein concentration in inflow; $C_{o,a}$, protein concentration in outflow; $V$, volume of fractionator; $Q_i$, flow rate.

In the second set of trials, changes in protein concentrations in culture tank water were monitored till no foam could be collected for 5 sets of combinations of HRTs and SAVs and each was conducted on a consecutive mode. Foam overflow height was 3 cm for all the 5 consecutive trials. Gas holdup, which is the fractional increase in column liquid height due to supply of aeration, was measured since it is essential for determination of the foam overflow height. Gas holdup was determined by measuring the height differences before and after supply of aeration.

**Foam fractionator**

A schematic diagram of the foam fractionator used in the present experiment is shown in Fig. 1. This foam fractionator is made of acrylic pipe with a diameter of 20 cm and a height of 120 cm. Water outlet was located near the bottom and inlet water was introduced on top of the column. This formed a counter-current flow pattern in the foam fractionator column. A 40-mm PVC elbow was installed at a 90-cm height for foam collection. Foam overflow height was controlled by changing the length of nipple pipe connected to the elbow. The foam outlet was connected to the collection bottle and a vacuum pump was used for quick collection of foam produced on top of the collection pipe. An air distribution system included an air blower, a pressure regulator, and an airflow meter (Dwyer instruments model RMA). Two coarse air stones with a diameter of 3.2 cm and a length of 9 cm were used to disperse air bubbles.

**Sample and analysis**

Samples were taken at 10, 20, 30 minutes and then at half hour intervals in culture tank water after the initiation of air supply for 5 consecutive trials to monitor changes in protein concentrations in culture tank water. For trials conducted on batch mode, 4 samples were taken at the inlet and outlet of a foam fractionator at intervals of 1-6 minutes. Protein analysis was conducted according to Lowry *et al.* (1951). TSS was measured according to standard methods (APHA 1995). Filter paper was rinsed successively 6 times with 20 m*l* distilled water for removal of salts left on the filter paper.

## 2. Results and discussion

Changes in protein concentrations in culture tank water when the foam fractionator was operated at different SAVs and a fixed HRT of 3 minutes is shown in Fig. 2. Initial protein concentrations were 34.8 ± 0.1 mg/*l*. Protein concentrations in culture tank water decreased faster at a

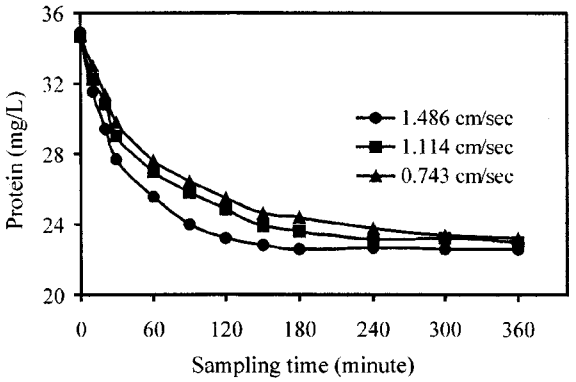


**Fig. 2. Changes of protein concentrations in culture tank water at three different superficial air velocities of 0.743, 1.114, and 1.486 cm/sec (HRT, 3 minutes; protein concentration, 34.8 mg/*l*; foam overflow height, 3 cm) in the simulated seawater recirculating aquaculture system.**

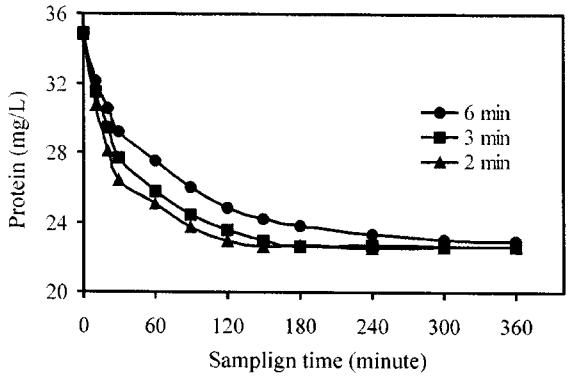


**Fig. 3. Changes in protein concentrations in culture tank water at three different hydraulic residence times of 2, 3, and 6 minutes (Superficial air velocity, 1.486 cm/sec; protein concentration, 34.7 mg/*l*; foam overflow height, 3 cm) in the simulated seawater recirculating aquaculture system.**

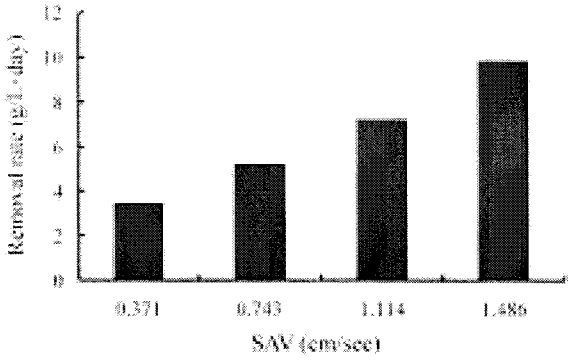


**Fig. 4. Protein removal rates at different superficial air velocities of 0.371, 0.743, 1.114, and 1.486 cm/sec (Protein concentration, 32.5 mg/*l*; HRT, 3 minutes; foam overflow height, 3 cm) in batch trials.**

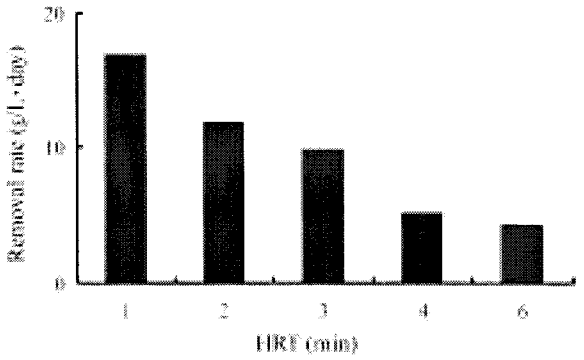


**Fig. 5. Protein removal rates at different hydraulic residence times of 1, 2, 3, 4, and 6 minutes (Protein concentration, 32.5 mg/*l*; superficial air velocity, 1.486 cm/sec; foam overflow height, 3 cm) in batch trials.**

higher SAV, with the lowest SAV corresponding to the lowest reduction rate in protein concentrations. Chen *et al.* (1994a) reported similar trends in freshwater systems.

Changes of protein concentrations in culture tank water at different HRTs are shown in Fig. 3. Superficial air velocity was set at 1.486 cm/sec. Lower HRT resulted in rapid removal of protein from culture tank water and thus the quick reduction of protein concentrations. Also, the reduction rates declined in treatment time, which were similar to the results obtained at different SAVs. In experiments done with direct fish culture water or synthetic wastewater, Chen *et al.* (1993a) also found that protein removal rates declined in treatment time. This decline of protein reduction rates must have been induced by the decline in protein concentrations in culture tank water.

The percentage of protein removal averaged 34.3%, which means incomplete removal of protein from culture tank water. The ratios of removed protein to initial protein concentrations were reported to be 11% (8-15%) by Chen *et al.* (1993a). These values were lower than the results obtained in the present experiment. Synthetic wastewater, which contained foam condensate, might have resulted in the discrepancies since the foam condensates contain much more available protein than original wastewater. These results also suggest that protein removal was limited and that not all the proteins detected by Lowry's method (1951) were surface-active since some proteins might not possess significant surface-active properties under certain conditions when considering their wide range of molecular structures (Chen *et al.* 1993a). This can be further confirmed by the results obtained in the present experiment that at a high SAV and a low HRT, no further reductions of protein concentrations were detected in the last 3-hours of operations though protein concentrations were still relatively high in culture tank water in trials conducted on consecutive modes (Figs. 2, 3).

In batch trials conducted at fixed initial protein concentrations of 32.5 mg/*l* and HRT of 3 minutes, protein removal rates increased with an increase of SAV (Fig. 4). Chen *et al.* (1994b) also found that the protein removal rate in the foam fractionation process is closely related to SAV and similar trends were reported. However, protein removal rates decreased with an increase of HRTs when foam fractionators were operated at a fixed SAV of 1.486 cm/sec (Fig. 5). These results were coincident with those reported by Suh *et al.* (2000b). Usually, a higher SAV increased the areas of air-water interface in a given time

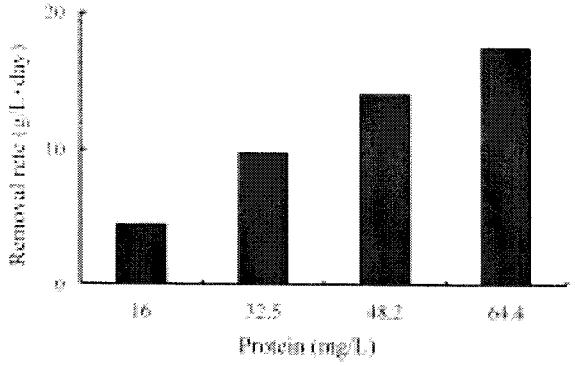


**Fig. 6. Protein removal rates at different initial protein concentrations of 16, 32.5, 48.2, and 64.4 mg/*l* (HRT, 3 min; superficial air velocity, 1.486 cm/sec; foam overflow height, 3 cm) in batch trials.**

period. This, as a consequence, increased the opportunities for proteins to be adsorbed on the air-water interface and then increased the protein removal rate. The lower HRT increased the contact opportunities of protein with air at the water-air interface and then increased the removal rates.

Fig. 6 shows protein removal rates on different initial protein concentrations. Protein removal rates increased with an increase in the initial protein concentrations. Protein is usually considered the main source of surfactants in aquaculture water (Chen *et al.* 1993a) when considering the high protein content of feed. Essentially all proteins are volatile solids (Timmons *et al.* 1995), which are considered the main substances that could be removed by foam fractionation (Weeks *et al.* 1992). The great impact of protein concentration on protein removal is easy to understand.

A linear increase of protein removal rates versus an increase in the initial protein concentrations in bulk solutions suggests that the protein removal rates followed a first-order process. Chen *et al.* (1994b) also reported that the protein removal rate is related to its concentration in the bulk solution as a first-order reaction in five-trial experiments, which were conducted in a freshwater system. Suh *et al.* (2000a) also reported an increase of protein removal rates at higher initial protein concentrations in a bulk solution. However, Suh *et al.* (1999) reported an exponential expression of the protein removal rates versus initial protein concentrations and they attributed this discrepancy to the different protein concentrations used and the different operating parameters.

Foam condensates produced in the 5 consecutive trials were collected till the separation process ceased. Protein concentrations in the foam condensates, foam overflow rates, time consumptions, and gas holdup data are summarized in Table 1. Higher SAVs resulted in greater foam flow rates but lower protein concentrations in foam condensates. Weeks *et al.* (1992) found the same trend in a freshwater aquaculture system. Protein concentrations in the collected foam condensates in the present experiment were about 13.6-26.3 times that of initial protein concentrations in culture tank water. These results show that protein enrichment in foam condensate can be substantial. HRT has significant effects on the foam overflow rate and the time consumption for protein removal in culture tank water. Time consumptions for removal of protein from culture tank water were about 2.5, 3, and 5.4 hours at an HRT of 2, 3, and 6 min, respectively. Protein concentration in foam condensate was higher at a lower HRT rate. However, the effects of HRT on protein concentrations in the foam condensates were not as great as the effects of SAV. Weeks *et al.* (1992) already reported that the water flow rate did not affect the removal of volatile solids over the range of 11.4-34.1 *l*/min tested in freshwater systems. Though the foam condensates were collected in trials conducted on a consecutive mode, which means that a continuous reduction of protein concentrations in culture tank water occurred in treatment time, these results still confirmed that high SAV would induce great protein removal and HRT has less effect on protein concentrations and the volume of foam condensates.

**Table 1. Summary of analysis results of foam condensates collected in 5 consecutive trials.**

| HRT (min) | SAV (cm/sec) | Protein (mg/*l*) | Time (hours) | Flow rate (m*l*/min) | Holdup (cm) |
|---|---|---|---|---|---|
| 6 | 1.486 | 610 | 5.4 | 12.0 | 5.6 |
| 2 | 1.486 | 474 | 2.5 | 32.6 | 5.6 |
| 3 | 1.486 | 524 | 3.0 | 25.4 | 5.6 |
| 3 | 1.114 | 607 | 3.9 | 16.0 | 4.2 |
| 3 | 0.743 | 915 | 5.6 | 6.8 | 2.8 |

The effects of foam overflow heights on performance of foam fractionators are shown in Table 2. The enrichment factor is defined as the ratio of protein concentrations in foam condensates to those corresponding values in the untreated bulk solutions. Protein concentrations and enrichment factors in the foam condensates increased with an increase in the foam overflow heights. However, foam overflow rates decreased with an increase of foam overflow heights. This is because that foam is swept out at a faster rate and at a lower foam overflow height, which

**Table 2. Performance data at different foam overflow heights (FOH) and fixed TSS concentrations of 120 mg/l and initial protein concentrations of 34 mg/l.**

| FOH (cm) | Protein in foam condensates (mg/l) | Enrichment factor | Foam flow rate (ml/min) |
|---|---|---|---|
| 1 | 178 | 4.7 | 76.4 |
| 3 | 524 | 13.8 | 25.2 |
| 5 | 816 | 21.5 | 15.6 |
| 7 | 920 | 24.2 | 12.3 |

does not allow excess water to drain from the foam. Higher foam overflow heights would increase protein concentrations and lower foam volume. Weeks *et al.* (1992), in a fresh water system, found the same trends but the differences were not as great as those found in the present experiment. Foam condensate used in the synthetic wastewater should have attributed to these discrepancies. Suh *et al.* (1995) also found that an increase of protein concentration in the foam condensate with an increase in the foam overflow height. These results suggested that high overflow heights may produce extremely concentrated foam condensate, but the production rates may be extremely low, so for practical application of foam fractionation in aquaculture systems, the foam overflow height should be selected so that the desired results, i.e. minimizing the effluent volume or maximizing substrate removal, could be obtained.

Gas holdup values were higher for higher SAVs. However, gas holdup values were the same at fixed SAVs with different HRTs. This indicates that gas holdup is not related to water flow rate through a foam fractionator column. This coincides with the results reported by Chen (1991).

## 4. Conclusion

Performance characteristics of foam fractionators are highly dependent on the operating factors including SAV, HRT, and foam overflow height. Protein removal rates increased with an increase in SAVs and a decrease in HRTs. High initial protein concentrations resulted in greater protein removal rates. Foam condensate production decreased and concentration increased as foam overflow height increased. Protein concentrations in the foam condensates collected from the 5 consecutive trials shows that water flow rates exert little effect on overall protein removal. Though high SAVs would increase the protein removal rate, extremely high SAVs may result in the formation of gas slugs (Timmons 1994) and reduce substance removal rates but this is out of the scope of this study. Also, lack of the performance data for foam fractionators in a seawater aquaculture system makes the interpretations of the data obtained in the present experiment difficult and the practical application of the present findings to aquaculture systems doubtful since large differences could be introduced by different managing strategies and dimensions of the foam fractionator.

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