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Performance of a Foam Fractionator in a Lab-scale Seawater Recirculating Aquaculture System

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The performance of a foam fractionator to remove TAN, NO_2, NO_3, TSS, protein, and PO_4-P at different superficial air velocities and foam overflow heights was evaluated in a lab-scale seawater recirculating system for culture of Korean rockfish (*Sebastes schlegeli*). The foam overflow rates increased with the increase of superficial air velocities, but decreased with the increase of foam overflow heights. Concentrations of all the water quality variables in the foam condensates increased with the increase of foam overflow height, but decreased with the increase of superficial air velocities. TSS, protein, and phosphate enrichment factors were within the range of 6.4-39.4, 1.6-7.3 and 1.2-3.9, respectively. Low values of TAN, NO_2, and NO_3 enrichment factors were obtained and they indicate that foam fractionation is not an effective way to remove dissolved inorganic nitrogen. The calculated maximum daily removal values for TSS and protein were 10.9 and 1.4 g, respectively.

Key words: Solids removal, Foam fractionator, Superficial air velocity, Foam condensate, *Sebastes schlegeli*

Introduction

Intensive aquaculture is under quick developmentrecently. Rirculating aquaculture systems are mainly developed to address the problems encountered in intensifying fish production. The success of a recirculating system depends largely on the treatment efficiency of waste generated in the system. The wastes of critical concern are ammonia and solids. Ammonia usually can be reduced to less toxic nitrogen forms or removed through biofiltration. The generated solids can be divided into two categories: settleable solids and non-settleable solids. Typically, the closed aquaculture systems are subject to an accumulation of fine suspended solids and dissolved organics (Timmons et al., 1995). Chen et al. (1993a) found that 95% of the suspended solids in recirculating aquaculture systems had a diameter less than 20 μ. These more difficult to control, finer, non-settable suspended solids cause the most serious problems in recirculating aquaculture systems. Fine solids were suspected responsible for fish kill in a recirculating system (Timmons et al., 1987). Others have reported the adverse effects of the solids on fish health and gill function (Stickeny, 1979; Wickins, 1980; Chapman et al., 1987; Major, 1998). Clogging of biofilter may be induced by high solids concentration in recirculating systems. Also, the solids could generatemore ammonia nitrogen and oxygen demand if not removed out of recirculating systems as soon as possible. The recommended limit of suspended solid concentration in a recirculating system is 15 mg/L (FIFAC, 1980; Reinemann, 1987; Timmons et al., 1987).

Foam fractionation has been used to remove solids and excessive nutrients in aquaculture systems. It is a gas/water interfacial phenomenon, which is accomplished by bubbling air or other gas through water to produce foam that can then be efficiently removed from the system (Timmons, 1994). Lomax (1976) found that, in terms of cost and effectiveness, the biofilter with foam fractionation was the best design combination after examination of several kinds of fish culture systems. Dwivedy (1973) found that foam fractionator removed solids and helped maintain pH in an oyster culture system. Besides, foam fractionator can serve as a gas-stripping unit, which is usually considered a necessity in recirculating aquaculture systems (Chen et al., 1993b).

Spotte (1979) has stated that the main factors affecting the efficiency of foam fractionation include

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hydraulic retention time, bubble size, air flow rate, diffuser submergence depth, foam overflow height, and the configuration of foam fractionator itself. For an existed foam fractionator, the factors affecting foam fractionation are air flow rate, water flow rate, and foam overflow height (Weeks et al., 1992).

Many researches evaluated the performance of foam fractionator in aquaculture systems (Chen, 1991; Chen et al., 1993b, c; Chen et al., 1994a, b; Suh and Lee, 1995, 1997; Suh et al., 1997; Suh et al., 2000; Suh et al., 2002). However, these researches used artificial wastewater or focused on limited number of parameters. Direct application of their findings to aquaculture still is not feasible. Weeks et al. (1992) investigated the feasibility of foam fractionation to remove suspended and dissolved solids form fish culture water in recirculating aquaculture systems, and the effects of different operational factors on the performance of the foam fractionation device. Suh and Lee (1997) evaluated the TSS, NH_3, TP, and TN removal efficiencies by a continuous foam separator in a simulated aquaculture system and concluded that application of foam fractionator in aquaculture system is practical. Recently, Suh et al. (2002) evaluated the performance of foam separator in a pilot-scale recirculating aquaculture system for culture of tilapia with the emphasis on protein, TSS, and COD removal. However, these researches were done in freshwater aquaculture systems. The foam fractionation process was evaluated most effective in marine application (Huguenin and Colt, 1989).The performance of foam fractionators in seawater aquaculture system needs to be studied.

In present study, the performance of foam fractionator to removesolids, protein, and other dissolved materials was evaluated at different foam overflow heights, air flow rates, and water flow rates in a lab-scale recirculating aquaculture system for culture of Korean rockfish (*Sebastes schlegeli*).

Materials and Methods

Recirculating aquaculture system description

The designed recirculating aquaculture system (Fig. 1) consists of a circular culture tank (volume, 0.8 m^3) and the low solids outlet water from the culture tank is let to two bead filters before going to the water sump. The excess outflow directly backs to the sump. From the sump, the water is pumped back to the culture tank. The flow rate to the culture tank is controlled by a bypass system. The outlet water of the bypass system directly flows to foam fractionator. The high solids outlet water from the culture tank goes to the sedimentation basin. A denitrification sand filter is connected to the sedimentation basin. The excess water from the sedimentation basin overflows to the water sump. Sodium bicarbonate solution is supplied to the culture tank by a feeding pump for pH compensation. Oxygen is supplied to culture tank and foam fractionator with air blowers. The characteristics of the system compartments are shown in Table 1.

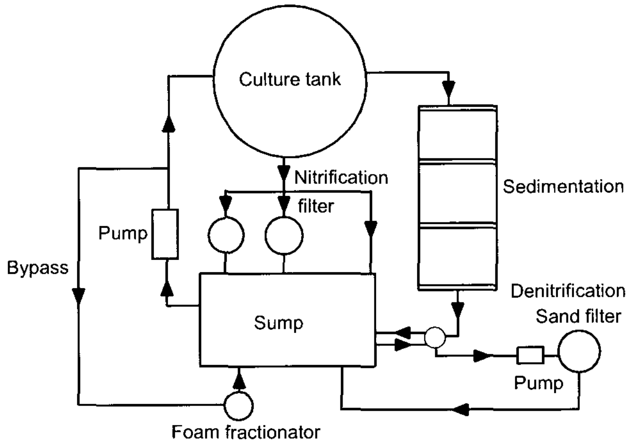

Fig. 1. Schematic diagram of the seawater recirculating aquaculture system. Arrows indicate the direction of water flow (not to scale).

Table 1. Characteristics of the compartments of the closed seawater recirculating system.

Compartment	Water volume (L)	Flow rate (L/h)	HRT (h)
Culture tank	600	1200	0.5
Bead filter	50	450	-
Sedimentation basin	210	60-120	1.7-3.5
Sand filter	25	3-60	0.5-8
Water sump	120	-	-
Fractionator	30	1200	-

This whole system was conditioned for 2 months before stocking by continuously feeding with synthetic wastewater. A total of 20 kg Korean rockfish (130 fish) with an average fish weight of 132.8 g was stocked to the culture tank on November 12, 2002. The daily feeding rate was 1-1.5% whole fish body weight. Daily water exchange rate was 3% of the whole system water volume.

Foam fractionation system and experimental procedure

A schematic diagram of the foam fractionator used in present experiment is shown in Fig. 2. This foam fractionator is made of acrylic pipe with a diameter of 20 cm and height of 120 cm. The water outlet is located near the bottom and the inlet water is introduced from the top of the column. This forms a counter-current flow pattern in the foam fractionator column. A 40-mm PVC elbow is fixed at 100-cm height for foam collection. The foam overflow height is controlled by changing the pipe connected to the elbow. The foam outlet is connected to a vacuum pump for quick collection of foam produced on the top of the collection pipe. Air distribution system includes an air blower, a pressure regulator, and an air flow meter (Dwyer Instruments, model RMA). Two air stones with a diameter of 3.2 cm and length of 9 cm are used to disperse the air bubbles. This kind of air stones is commonly used in aquaculture systems and usually is considered as coarse air stone.

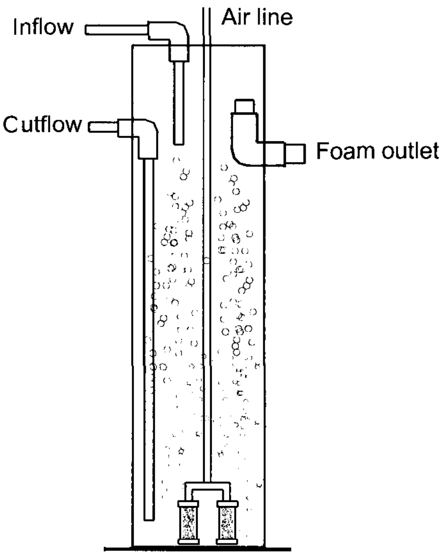

Fig. 2. Schematic diagram of the foam fractionator used in the seawater recirculating system.

This foam fractionator was evaluated at fixed hydraulic residence time (HRT) of 2 min, 3 different superficial air velocities (SAVs) of 0.743, 1.114, and 1.486 cm/min, and 4 foam overflow heights of 1, 3, 5, and 7 cm. Performance of the foam fractionator at different HRT was not evaluated in the present study. Weeks et al. (1992) already found that water flow rate through the foam fractionator column did not affect the amount of solids removed in freshwater aquaculture system. Besides, the water was let to the fractionator through a bypass system which is mainly used for adjust the water flow rate to the culture tank but not foam fractionator.

Sampling and analysis

Foam condensate samples were collected after 2-month operation of the foam fractionator in the lab-scale recirculating aquaculture system. Foam was collected till a sample volume large enough to analyze, and the operational factors were readjusted for the next trial. The samples were collected, analyzed, and replicated three times for each combination of operational factors. Culture system water samples also were collected for each trial.

Protein analysis was conducted according to Lowry et al. (1951). This method is suitable for measurement of low protein concentrations. Bovine serum albumin powder dissolved in NaCl solution was used as the protein standard. TSS wasmeasured according to standard methods (APHA, 1995). The filter paper was rinsed successively 6 times with 20 mL distilled water for removing the saltsleft on the filter paper. TAN, NO_2-N, NO_3-N, and PO_4-P were analyzed using the methods described by Strickland and Parsons (1972). Later, the data were expressed as the enrichment factors for each parameter. Enrichment factor is defined as the ratio of the values in foam condensates to corresponding values in the culture system water.

Results and Discussion

Table 2 shows the mean and range of water quality parameters in the culture system water during the experimental period. Total ammonia nitrogen and NO_2-N concentrations were low and within the ranges reported in the well-developed recirculating aquaculture system (arbiv and van Rijn, 1995; Kamstra et al., 1998).

TSS enrichment factors (EFs) in the foam condensates collected at different superficial air velocities

Table 2. Water quality parameters in the culture system water during the experimental period.

Parameters (mg/L)	Mean (mg/L)	Range (mg/L)
TAN-N	0.32	0.21-0.45
NO_2-N	0.45	0.38-0.69
NO_3-N	19	16-23
TSS	33	26-34.7
Protein	37.3	34.8-39.1
PO_4-P	27.9	26.3-29.8

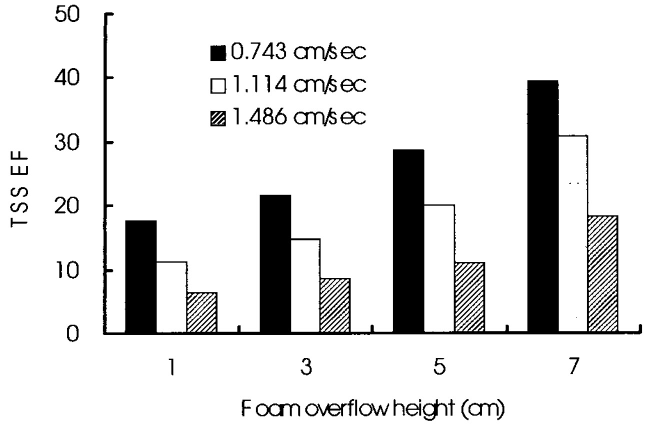

Fig. 3. Effects of foam overflow heights and superficial air velocities on TSS enrichments in foam condensates as indicated by enrichment factor (EF).

and foam overflow heights are shown in Fig. 3. Differences of TSS concentrations in the collected foam condensates are significant among the different foam overflow height treatmentsat the lower SAV of 0.743 cm/sec. TSS concentrations increased with the increase of foam overflow heights for each treatment at different superficial air velocities. This indicates the great effect of foam overflow height on TSS concentrations. The effects were greater for lower SAV treatment than those for higher SAV treatments. TSS concentrations increased with the increase of SAV at each foam overflow height. Enrichment factors ranged from 6.4 to 39.4. Weeks et al. (1992) found that the TSS enrichment factors were within the range of 17-40 and demonstrated the same trends of change of TSS concentrations in the foam condensates followed change of SAVs and foam overflow heights. Chen et al. (1993b) also found an enrichment factor of more 10 in freshwater aquaculture systems. These results show that TSS enrichment in the foam condensate could be substantial.

The effects of different foam overflow heights and SAVs on protein concentrations in the collected foam condensates are shown in Fig. 4. The protein enrichment factors ranged form 1.6-7.3. These values were much lower than TSS enrichment factors. Also, the protein concentrations in the foam condensates increased with the increase of foam overflow heights at each SAV and higher SAV induced lower protein concentrations in foam condensates at each overflow height as indicated by the enrichment factors. The effects of overflow heights on enrichment factors were greater for lower SAV treatments than those at higher SAV. These low enrichment factors indicate that not all the proteins detected by Lowry's method are surface-active. Chen et al. (1993c) reported that, on average, only 11% of the total protein detected was surfactants.

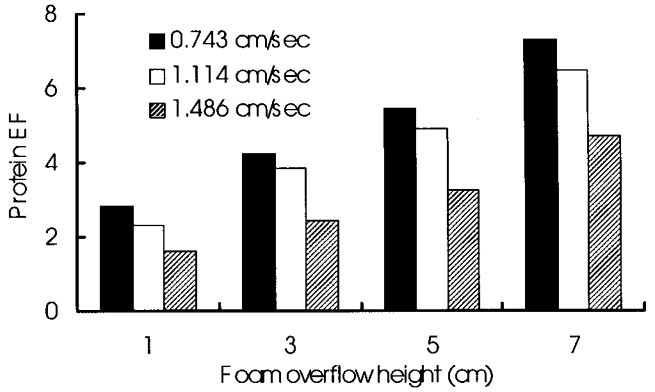

Fig. 4. Effects of foam overflow heights and superficial air velocities on protein enrichment in foam condensates as indicated by enrichment factor (EF).

Reactive phosphorus enrichment factors showed the same trends as for TSS and protein (Fig. 5). The values were within the range of 1.2-3.9. However, the differences of PO_4-P concentrations in the foam condensates at higher foam overflow height treatment were not so great as for TSS and protein. Hussenot et al. (1998) also found that foam fractionation apparatus was effective at trapping dissolved mineral materialssuch as phosphates.

The decrease of TSS, protein, and phosphate-concentrations in the foam condensate as a result of increase of SAV was due to the fact that at higher

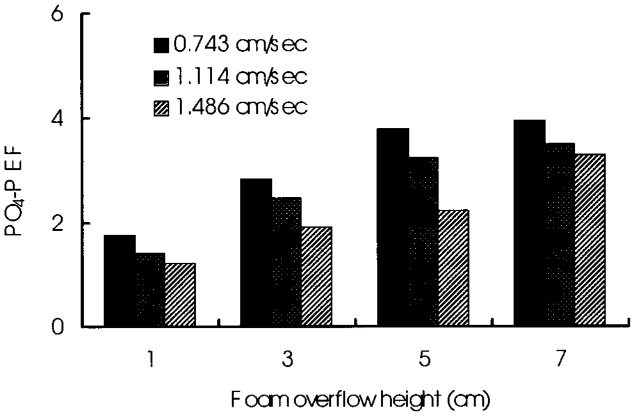

Fig. 5. Effects of foam overflow heights and superficial air velocities on PO_4-P enrichment in foam condensates as indicated by enrichment factor (EF).

SAV the foam was swept out at a faster rate, which did not allow excess water to drain from the foam. High foam overflow height increased the time need for foam to be drained out of the fractionator column and consequently increased the time the foam had to drain water. The TSS, protein, and phosphorus concentrations were significantly lower in foam condensates collected at lower foam overflow height treatments. which means that relatively dilute foam condensates were produced at low foam overflow height.

TAN, NO_2-N, and NO_3-N enrichment factors were shown in Fig 6-8. No significant differences of TAN enrichment factors were found for all the treatments. Relatively greater differences of NO_2-N enrichment factors were found among different foam overflow height treatments at each SAV applied. Also, the higher SAV induced lower values of NO_2-N enrichment factors. Changes of NO_3-N enrichment factors showed the same trends as for NO_2-N. However, the TAN, NO_2-N, and NO_3-N enrichment factorswere relatively low when compared with TSS and protein enrichment factors.

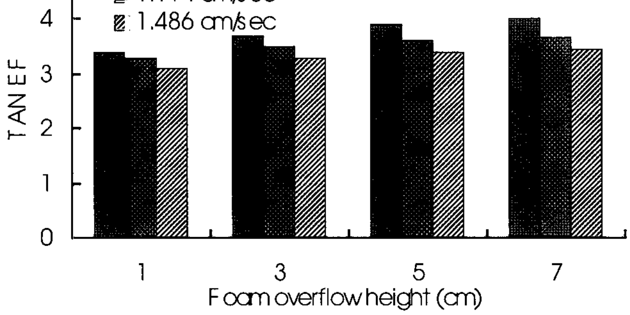

Fig. 6. Effects of foam overflow heights and superficial air velocities on TAN enrichment in foam condensates as indicated by enrichment factor (EF).

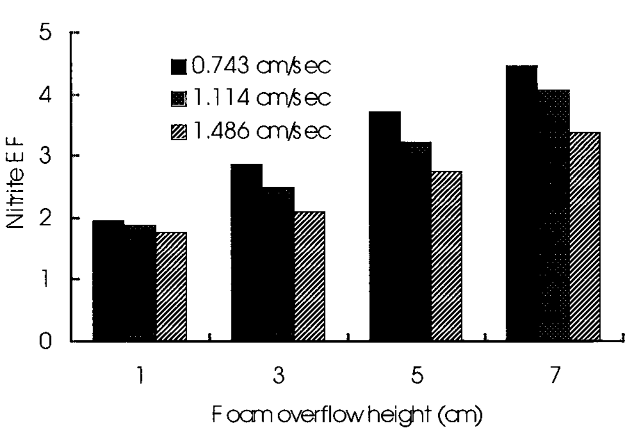

Fig. 7. Effects of foam overflow height and superficial air velocities on NO_2-N enrichment in foam condensates as indicated by enrichment factor (EF).

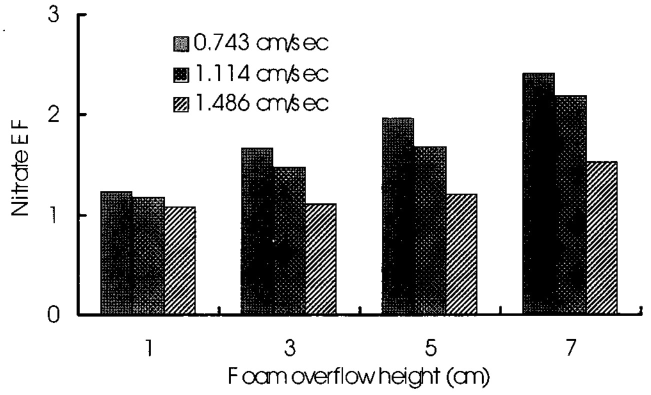

Fig. 8. Effects of foam overflow heights and superficial air velocities on NO_3-N enrichment in foam condensates as indicated by enrichment factor (EF).

These results show that foam fractionation is not an effective way for removal of dissolved inorganic matters. Spotte (1979) already concluded that within the common pH ranges, foam fractionation does not reduce the level of ammonia in aquarium water. Hussenot et al. (1998) also found lower enrichment factors for TAN, NO_2-N, and NO_3-Nin marine aquaculture systems. However, Suh and Lee (1997) reported higher removal efficiency of TAN and NO_2-N in a simulated aquaculture system and concluded that foam fractionation could be a very effective way for TAN and NO_2-N removal. This should be mainly due to the different operating factors used in their experiment, especially the small dimension foam fractionator column used and the high HRT and SAV applied in their experiment. There are indications that small dimensional change and differences in operating parameters can have large impacts on performance (Know, 1971; Huguenin and Colt, 1989).

Table 3 summarizes the foam overflow rates, calculated data for daily removal of TSS, and protein by foam fractionator. The daily removals of TAN, NO_2-N, NO_3-N and PO_4-P were not shown here due to the low values calculated, and this showsthat the low efficiency of foam fractionator for reduction of these variables. Foam overflow rates decreased with the increaseof foam overflow heights at each SAV treatment. The foam overflow rates were higher for

Table 3. Foam overflow rate (FOR) and calculated removal rates of different water quality variables at different superficial air velocity (SAV) and foam overflow height (FOH)

SAV (cm/sec)	FOH (cm)	TSS (g/day)	Protein (g/day)	FOR (mL/min)
0.743	1	5.67	0.92	6.8
0.743	3	3.07	0.60	3.0
0.743	5	1.93	0.37	1.4
0.743	7	1.29	0.19	0.6
1.114	1	7.10	1.47	9.2
1.114	3	4.73	1.23	5.0
1.114	5	3.60	0.88	3.8
1.114	7	1.79	0.37	1.6
1.486	1	10.94	2.78	36.2
1.486	3	5.01	1.44	12.4
1.486	5	3.76	1.10	7.1
1.486	7	2.15	0.56	2.5

high SAV treatments than low SAV treatments when compared at the same overflow height. The effect of foam overflow heights on foam overflow rate was greater for higher SAV treatments than those at lower SAV treatments. The foam overflow rates were quite higher for lower overflow height treatment than those at higher overflow height treatment, and this is especially evident for higher SAV treatment. Weeks et al. (1992) found same trends in freshwater aquaculture system. Though the concentrations of TSS and protein concentrations were higher in foam condensates collected from higher overflow height treatments, the calculated daily removals of these variableswere greatly affected by the foam overflow rates. Lower foam overflow height resulted in greater removal of these variables when compared with high foam overflow height treatments. These results indicate that using minimal overflow heights variables in foam condensate may be only marginally concentrated than those in the culture water, and high overflow heights may produce extremely concentrated foam condensates, but the foam production rate may be extremely low. For practical application of foam fractionator in aquaculture systems, extremely low foam overflow height such as 1 cm height, especially when combined with high SAV, should not be used in order to minimize the volume of wastewater discharged. However, one could select the operating factors to satisfy their desired result, as minimizing the wastewater volume or maximizing variables removal.

In summary, the performance of foam fractionator to remove TAN, NO_2, NO_3, TSS, protein and PO_4-Pat different superficial air velocities and foam overflow heights was evaluated in a lab-scale seawater recirculating system for culture of Korean rockfish. The foam overflow rates increased with increase of superficial air velocities but decreased with the increase of foam overflow heights. This trend was more obvious at high superficial air velocities tested. Concentrations of all the water quality variables in the foam condensates increased with the increase of foam overflow height and the increase of superficial air velocities. Lower foam overflow height resulted in more dilute foam condensates. The TSS, protein, and PO_4-Penrichment factors were within the range of 6.4-39.4, 1.6-7.3 and 1.2-3.9, respectively. Low values of TAN, NO_2, and NO_3 enrichment factors were obtained and this indicated that foam fractionation is not an effective way for removal of dissolved inorganic nitrogen. The calculated maximum daily removal values for TSS and protein were 10.9 and 1.4 g, respectively. So, foam fractionation process is very effective for solids trapping in the foam condensate. However, to the observation of the authors, the solids remained in the filtrate even after being filtered through 0.45-micron filter papers. So, the detailed analysis of the size distribution of solids in the foam condensate will be helpful for accurate evaluation of which kind of solids could be removed with foam fractionator. Also, lack of the performance data of foam fractionator in seawater recircluating aquaculture system makes the interpretations of the data obtained in the present experiment difficult andthe practical application of the findings found here to other aquaculture systems doubtful since large differences could be introduced by the different managing strategies and dimensions of the foam fractionator.

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