The effect of surfactants on low water cut oil–water flows in large diameter pipelines

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ABSTRACT

Free water layer can be present at the pipe wall even at very low input water volume fraction ($\leq 20\%$), and this free water layer causes extensive corrosion problems in oil-water flow. Addition of surfactant can enhance oil-water mixing, thus reducing corrosion.

Flow characteristics and the effect of surfactant have been determined in a 10-cm diameter horizontal Plexiglass pipeline at input water cuts of 5%, 10%, 15%, and 20%. ASTM substitute seawater and oil (viscosity 3 cP at 25°C) were used at superficial liquid velocities ranging from 0.4 to 3.0 m/s.

Water holdup is strongly affected by superficial mixture velocity and existence of surfactant. Without addition of surfactant, at mixture velocity up to 1.2 m/s, no water can reach the top of the pipe and no oil can contact the bottom of the pipe. For the mixture velocity range of 1.6 ~ 2.0 m/s, large percentage of oil is entrained into the water and reaches the bottom. Above 2.0 m/s, the composition of oil-water mixture across the pipe cross section is no longer conspicuous except for 20% input water cut.

Oil and water begin to mix at higher superficial velocity with a decrease of input water cut. They are easier to be mixed and the area occupied by oil-water mixture is larger when surfactant is added.

The input water cut and mixture velocity have influence on the velocity distribution. Addition of surfactant does not affect velocity distribution significantly for the flow conditions investigated. At all water cuts studied, the water layer moves at lower velocity than oil layer below an input mixture velocity of 1.2 m/s.

For the whole range of mixture velocity tested, input water cuts and addition of surfactant have no significant effect on pressure gradient.

1. INTRODUCTION

The increase in offshore drilling and production results in an increase in the transportation of well fluids through pipelines over long distance. Most well fluids are composed of oil and gas and frequently contain water. Water fractions will tend to increase over the productive life of the well. Therefore, water must be considered when predicting flow behavior that will be used in the designing of wells, production facilities and pipelines.

Furthermore, the internal corrosion in oil production and transportation is always associated with water, and the likelihood of corrosion generally increases with the volume fraction of water (Wicks et al. 1975). Wicks et al. found that corrosion in pipelines was usually dominant in areas where there was a possible accumulation of water. In highly turbulent flow the corrosion rates where much lower than when the flow was intermittent. This was due to formation of a separated water phase at the bottom of the pipes. They studied the minimum oil velocity required to entrain the water droplets. Equations were proposed to calculate the minimum oil velocity required entrain the liquid droplets.

Many oil fields are located in remote areas such as Alaska. The pipelines are in deep water or covered with snow, thus making the maintenance, repair, and replacement costs of pipelines costly. Using corrosion inhibitors is an economically feasible and important way to curb corrosion. Corrosion inhibitors are substances containing organics that adsorb to the metal surface and form a protective film to prevent corrosion. The effectiveness of the inhibitor depends on the pipeline material, the inhibitor composition, and type of flow. It is necessary to introduce the inhibitor into the phase in contact with the pipe wall and this can be accomplished only if flow patterns and phase distributions under different conditions are known.

A study of the flow regimes possible in horizontal liquid-liquid flow was experimentally conducted by Russell et al. (1959). The flow patterns observed were bubble, stratified and mixed flow. Four flow patterns were defined by Charles et al. (1961): water droplets in oil, concentric water with oil flow in the core, oil slugs in water and oil bubble in water. Oglesby (1979) gave a detailed report on eight flow patterns observed in oil-water flows; segregated, semi-segregated, semi-mixed, mixed, slug, annular, semi-dispersed, and homogeneous flow.

A new classification for oil-water flow patterns was proposed by Trallero et al. (1996). Here the oil-water flows are classified in two categories: segregated flow and dispersed flow. Segregated flow patterns include the stratified flow and stratified flow with some mixing at the interface. These correspond to the segregated flow and semi-segregated flow of Oglesby. Four flow patterns have been characterized in dispersed flows. They are, oil in water and water, oil in water emulsion, water in oil and oil in water and water in oil emulsion.

Malhotra (1995) has reported three distinct flow patterns (bubble, semi-segregated and semi-mixed) for 2 cP oil-water mixture in a 10 cm diameter horizontal pipeline. Bubble flow is observed for a mixture velocity in the range 0.4 ~ 0.6 m/s and an input oil percentage less than 10%. Semi segregated flow is observed for an oil cut above 20% and mixture velocity in the range 0.4 ~ 0.8 m/s; above 0.8 m/s semi mixed flow is observed. The volume occupied by the oil/water dispersion increases with increase in mixture velocity. For velocities greater than 1.4 m/s almost homogenous mixture is obtained.

It is found that addition of surfactants to the corrosion inhibitor formulations can increase the dispersibility of the inhibitor and help increase its effectiveness (Tulshyan, 1997). Surfactant could also reduce the surface and interfacial tension of the fluids and enhance the oil-water mixing and maybe the formation of emulsions (Shi, 1999). Therefore, adding the surfactant is another method for preventing corrosion in multiphase pipeline. However, the experiments carried out by Shi et al. did not included low water cut conditions (< 20% input water volume fraction).

In this paper, experimental results on pressure gradient, water holdup and velocity profiles are given, and the effect of surfactant on the flow characteristics for low input water cuts is discussed.

2. EXPERIMENT SETUP AND PROCEDURE

The 10-cm I.D., 40-m long, low pressure, experimental flow loop is shown in Figure 1. An oil/water mixture with specific composition is stored in a 1.2 m^3 stainless steel storage tank (A). The tank is equipped with two 1 kW heaters (B) and stainless steel cooling coils to maintain a constant temperature. The mixture is pumped through the system using a 5-hp centrifugal pump (C) equipped with a variable speed motor, which also controls the liquid flow rate. A T-junction fitted with a ball valve is set just after the pump. Liquid samples are withdrawn from this ball valve during the experiments to ensure that the appropriate water fraction is maintained. Bypass line (D) serves to agitate the oil/water mixture in the tank. The flow rate is measured using an orifice plate. The system is deoxygenated and maintained at a pressure of 0.13 MPa using carbon dioxide supplied from storage facility (E).

The oil/water mixture flows through a 3 m long flexible hose (G), which allows the inclination to be set at any angle, and then enters the 10-cm I.D., 18-m long Plexiglass pipeline where flow pattern, pressure gradient, and flow characteristics are measured. The oil/water mixture then returns to the tank and is recirculated.

Figure 2 shows a schematic of the 2-m long test section. The sampling/Pitot tube (B) is used to determine the water holdup/velocity profile. . The pressure gradient is measured using a manometer. A Panasonic super-VHS camera was used to visualize the flow. Red water soluble dye is added in the oil to help the observation.

The test matrix is described in Table 1.

Table 1 Experimental Test Matrix

Liquid Phase	Oil (3 cP at 25° C), Substitute ASTM seawater
Surfactant Concentration	10 ppm
Liquid Velocities	0.4 ~ 3.0 m/s
Input Water Cut	0%, 5%, 10%, 15%, 20%
Pressure	0.13 MPa
Temperature	25° C

A water dispersible surfactant, Witcomul 4016 (alkoxylated alkyl phenol), was used as surfactant in the experiments. It reduces interfacial tension between oil and water from 33.4 to almost zero at 10 ppm. This may suggest that an emulsion be being formed. It is found that the surfactant concentration keeps constant during the test runs.

3. RESULTS AND DISCUSSION

3.1 *in situ* Water Distribution

At a mixture velocity of 0.6 m/s and below, stratified or segregated flow pattern was observed. Figures 3 ~ 7 show the *in situ* water distribution curves for mixture velocities of 0.8, 1.2, 1.6, 2.0, 3.0 m/s, respectively. The ratio of the thickness of the liquid layer from the bottom of the pipe to the diameter of the pipeline, h/D, is plotted against the *in situ* water percentage. The experimental error was within 10%.

In Figure 3, at a low mixture velocity of 0.8 m/s for 15 and 20% input water, water and oil are flowing in two layers with little mixing at the interface. This flow pattern is called semi-segregated or semi-stratified. For input water cuts of 5% and 10%, since there is some oil penetrating to the bottom, the flow pattern changed to semi-mixed.

As the mixture velocity is increased to 1.2 m/s shown in Figure 4, at a composition of 20% input water cut, the bottom water percentage is 100. As the sampling tube is moved up to a h/D of 0.1, the water percentage decreases to 90. It then decreases to 82% and 60% at h/D 0.2 and 0.3 respectively. A thin mixed oil-water layer is observed between the h/D of 0.2 and 0.4. Oil layer is observed above an h/D of 0.55 and water layer is below 0.35. However, for the other three input water cuts, it seems the mixture velocity has a higher effect on oil/water mixing. For an input water cut of 15%, it is seen that no free water layer appears and there is 30 % oil at the bottom of the pipe. Above an h/D of 0.65, an oil layer exists. At lower input water cut of 10%, oil layer stays above an h/D of 0.75. The bottom oil concentration is 50%. More oil appears at the bottom for the lowest input water cut of 5%. There is 65% oil reaching the bottom and oil layer flows above an h/D of 0.75.

Figure 5 shows the distribution of water for a mixture velocity of 1.6 m/s. 20% oil reaches to the bottom and water reaches an h/D of 0.85 for an input water cut of 20%. At lower water cut of 15%, there is more oil than water at the bottom and the water gets

entrained up to an h/D of 0.95. For the other two input water cuts, the concentration of oil at the bottom is much larger than the water concentration and water appears also at h/D of 0.95.

For the mixture velocity 2.0 m/s in Figure 6, oil and water mixture is fairly well mixed across the whole pipe cross section for the three input water cuts of 5%, 10% and 15%. However, it can be seen that at the bottom of pipe, there is always larger amount of water existing for input water cut 20%. This is reasonable compared with the other lower input water cuts because usually the lower the input water cut, the easier it is for the water to be entrained into the oil. The oil-water mixture is seen to be homogeneous at a mixture velocity of 3.0 m/s for the four input water cuts. These results are shown in Figure 7. Therefore, from Figures 3 to 7, it can be concluded that mixture velocity strongly affects the water distributions, and the lower the input water cut, the easier it is to get the water to be entrained into the oil. 20% water is an exception.

Figure 8 shows the effect of addition of 10 ppm surfactant at a mixture velocity of 1.2 m/s. Compared to Figure 4, it is seen that surfactant slightly affects the oil/water distributions. For the 20% input water cut, 5% oil is found at the bottom of the pipe and water is entrained 1 cm higher. For 5 and 10% input water cuts, the bottom oil concentration increases by 10% and 20% respectively and water is entrained 2 cm higher. For 15% input water cut, the effect of the surfactant is more conspicuous. The water is entrained to an h/D of 0.85, 3 cm higher than that of without surfactant. There is 40% oil at the bottom, 10% higher than without surfactant.

For the 1.6 m/s mixture velocity, Figure 9 shows similar trends. Again, there is a large amount of water at the bottom for 20%. However, for the other three water cuts, bottom oil concentration is now larger than the water concentration, and more water is present towards the top part of the pipe. At this velocity and surfactant concentration, the profiles for the 5, 10, and 15% water cuts show a relatively good mixing across the pipe. It is seen clearly from Figure 10 that the water distribution curves for the three low input water cuts tend to be uniform, but the bottom water concentration is still very high at 60% for 20% input water cut. Comparing Figure 9 and 10 with 5 and 6, it is also seen that surfactant has little influence on the bottom water concentration for 20%.

Vedapuri (1999) found that at input water cut of 20%, the water layer tends to stratify and no much mixing is observed between oil and water up to a mixture velocity of 1.6 m/s in his 10-cm I.D., slightly inclined system of ± 2°, ± 5°, ± 15°.

3.2 *in situ* Velocity Distribution

Figures 11 ~ 13 show the *in situ* velocity profiles for input water cut of 5%, 10%, and 15% respectively. Figure 14 and 15 give the corresponding results for addition of 10 ppm surfactant for 5% and 10%. The *in situ* velocity of oil-water mixture was taken using a Pitot tube across the cross section. The experimental error was within 10%.

It is seen from Figure 11, the distribution curves obtained for both 0.4 and 0.8 m/s are relatively flat and very similar. Oil and water flow as two layers in this mixture velocity range. The oil layer is above an h/D of 0.2 as shown in Figure 3, so that the oil layer flows faster than the water layer. Visual observation also showed that the oil layer moved much faster.

Increasing mixture velocity to 1.2 m/s, it is seen that the *in situ* velocity changes gradually from about 0.8 m/s to 1.3 m/s between a h/D of 0.1 to 0.3. This would indicate that the oil and water here are becoming mixed. As the velocity is increased to 1.6 m/s there is a change in the nature of the distribution curves. The velocity profile of 2.0 m/s is very similar to that of 1.6 m/s and both of them are almost symmetrical. Dispersed flows were observed at these two velocities. At highest velocity of 3.0 m/s, the velocity profile is asymmetrical. Homogeneous flow patterns were observed here.

It is seen that with increasing mixture velocity, the in situ velocity profiles tend to behave like the single phase turbulent velocity profiles. This is due to the fact that at low mixture velocities of 0.4 and 0.8 m/s, water and oil are not mixed. The 5% water occupies a very small fraction of the pipe and moves at the pipe bottom, while the 95% pure oil occupies most of the space and moves above the water. Therefore, the velocity profiles of this oil-water mixture is almost same as those of 100% pure oil. Increase the mixture velocity leads to the penetration of water into oil and the change of velocity profiles.

Figure 12 shows the results for input water cut of 10%. For velocity of 0.4 and 0.8 m/s, again, it is clearly seen that the oil moves faster than the water. The velocity profiles for 1.2 m/s and 1.6m/s are similar. Mixed flow patterns were observed with the well-mixed dispersions were between a h/D of 0.3 to 0.7, and the thin free oil layers flowed above it. The oil-water dispersions moved faster than the oil layers. For mixture velocities of 2 m/s and above, velocity distributions are different and homogeneous flow patterns were obtained. The velocity profiles for an input water cut of 15% is very similar to that of 10% seen from Figure 13.

When 10 ppm surfactant was added to the system, Figure 14 shows that for 5% input water, *in situ* velocity profiles do not change much for the mixture velocities. When input water cut is increased to 10% shown in Figure 15, there is again not much difference between the results of without surfactant and with the surfactant. Also, there are the same results for an input water cut of 15%. It is concluded that the 10 ppm surfactant does not affect the velocity profiles much for the three low water cuts.

3.3 Pressure Gradient

The effect of 10 ppm surfactant on pressure gradient is shown by Figure 16. The dot lines give the results with surfactant. The experimental error is about 10%.

From Figure 16, for the mixture velocity of 0.8 m/s, the pressure gradient is almost constant when the input water cut is increased from 0 to 20% without surfactant. There is also no significant difference in the pressure gradient for the input water cuts of 0, 5%, 10%, and 15% with and without surfactant in the system. For the 20% input water cut, the pressure gradient increases a little when surfactant is added.

When the mixture velocity is increased to 1.2 m/s, again, no significant effect of surfactant and input water cut on the pressure gradient below an input water cut of 10%. Increasing the input water cut from 0% to 10%, the pressure gradient value remains at value close to 140 N/m^3. Further increase the input water cut, the pressure gradient gradually increases to 150 N/m^3 at 15% and 165 N/m^3 at 20%. With addition of surfactant, the corresponding values are 165 N/m^3 and 185 N/m^3 respectively.

For the mixture velocity of 1.6 m/s and above, it is also seen that surfactant affects the pressure gradient a little in all four input water cuts. Therefore, the effect of surfactant, if any, is very insignificant and within limits of experiment error. This indicates that the water soluble surfactant would not play an important role in low water cut situations.

4. CONCLUSIONS

- The *in situ* water percentage is affected by the input water cut, mixture velocity and the addition of water soluble surfactant. The less the input water cut, the easier the water get entrained to the oil for the input water cuts below 20%.

- The input water cut, mixture velocity and addition of surfactant have no significant effect on velocity profiles for the low input water cuts. The water layer moves at lowest velocity for the input water cuts below 20%.

- The water soluble surfactant at 10 ppm concentration does not influence the pressure gradient to a noticeable extent at low water cut of 20% and below.

- Oil and water are much more difficult to mix at 20% input water cut compared with the other input water cuts investigated.

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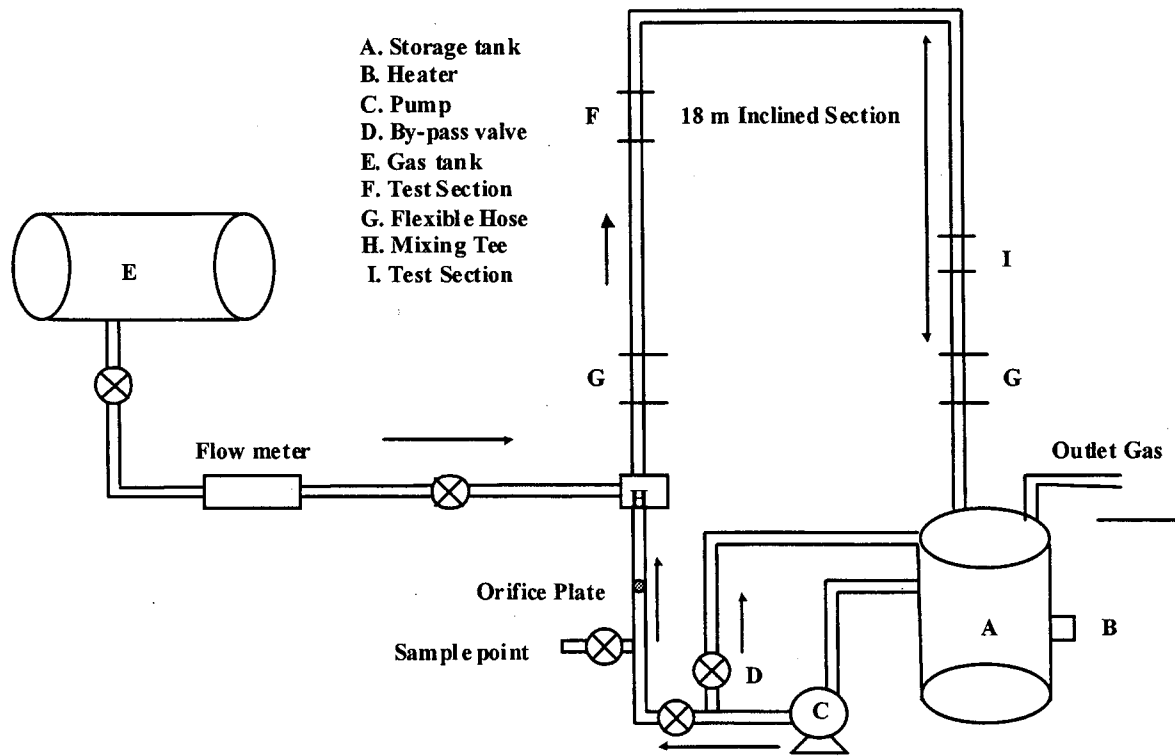(9) Wicks, M and Fraser, J.P., Entrainment of Water by Flowing Oil. Materials Performance , pp.9~12, May,1975.

A. Storage tank
B. Heater
C. Pump
D. By-pass valve
E. Gas tank
F. Test Section
G. Flexible Hose
H. Mixing Tee
I. Test Section

F

18 m Inclined Section

I

G

G

Flow meter

Outlet Gas

H

Orifice Plate

Sample point

D

C

A

B

Figure 1   Experimental Layout of the Flow Loop

A. ER Probes
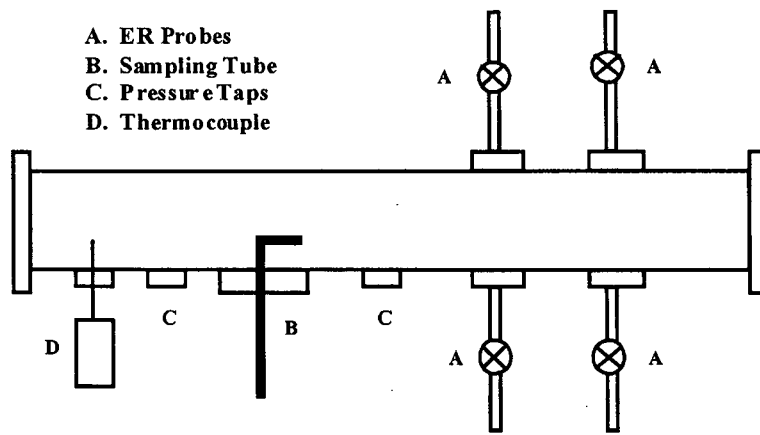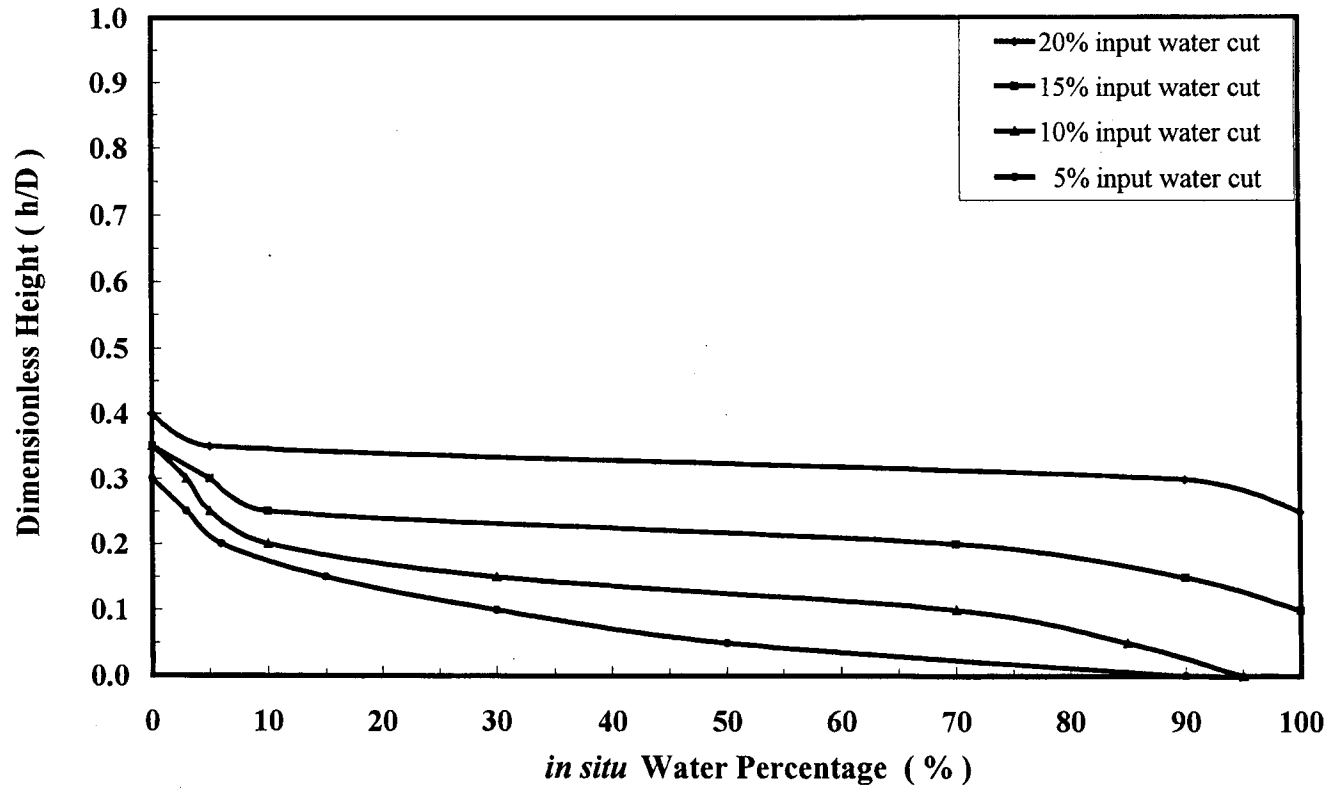B. Sampling Tube
C. Pressure Taps
D. Thermocouple

Figure 2 Test Section

Figure 3 Variation of Water Percentage with Vertical Position
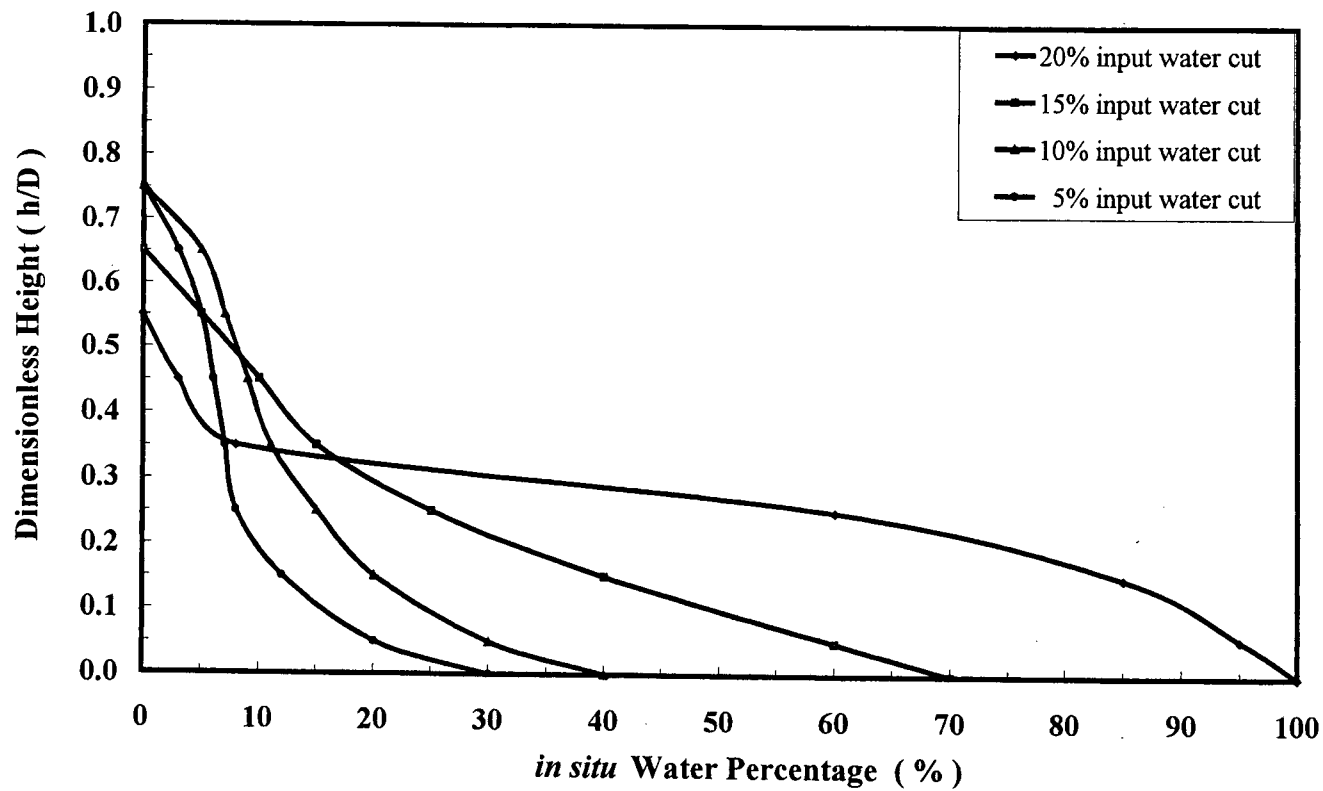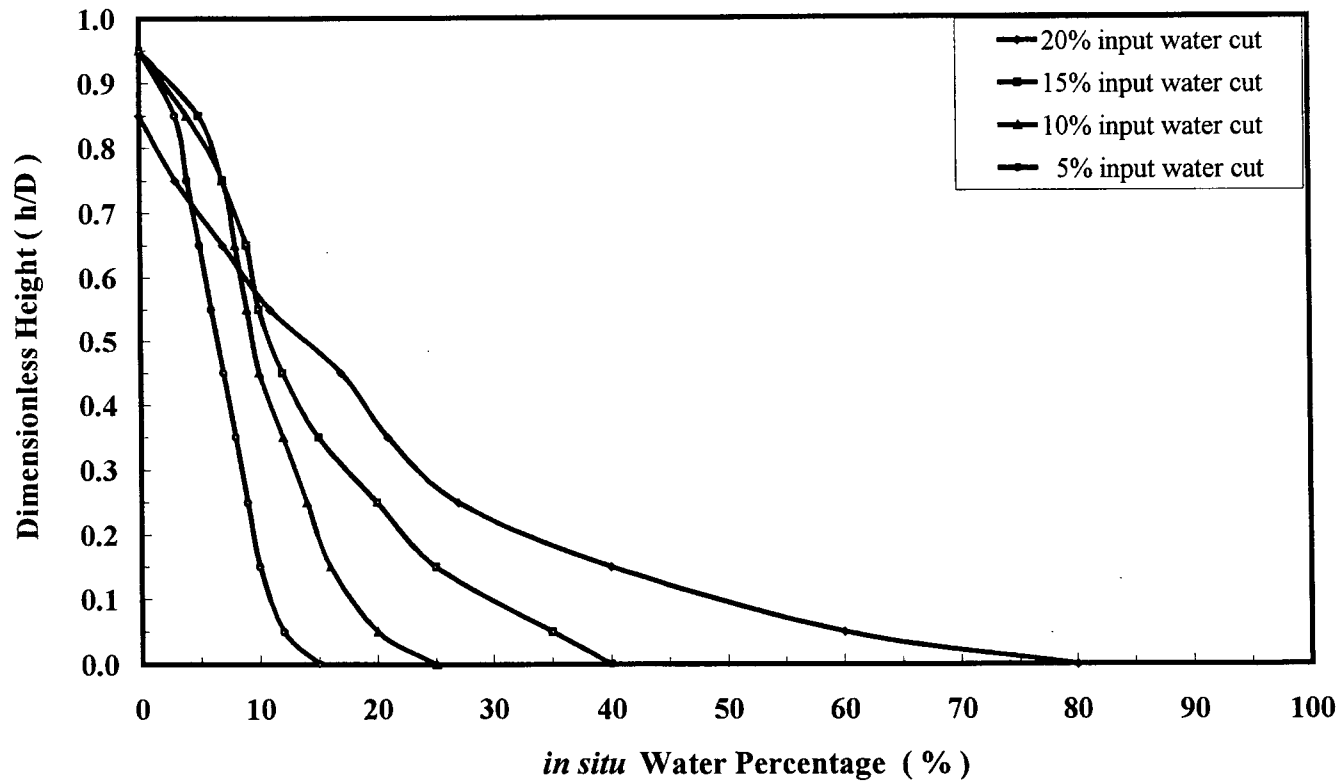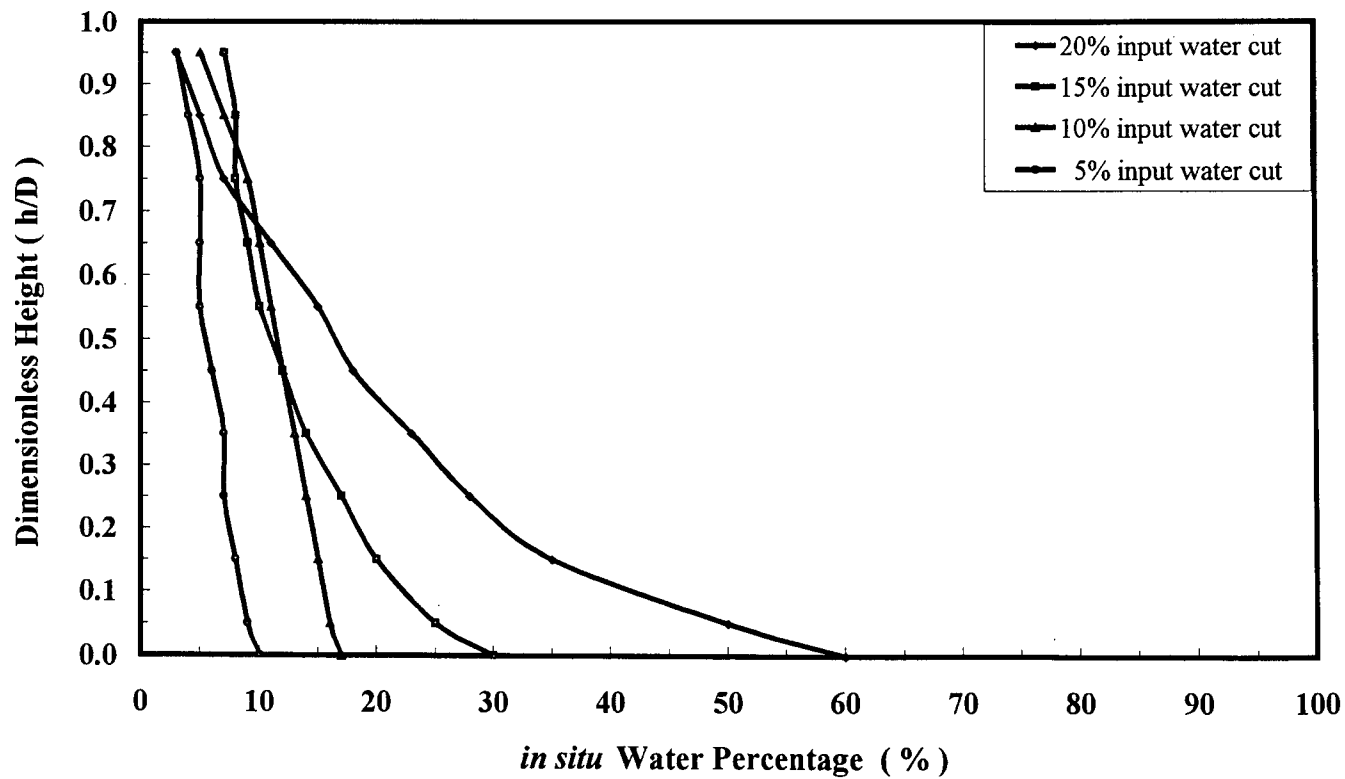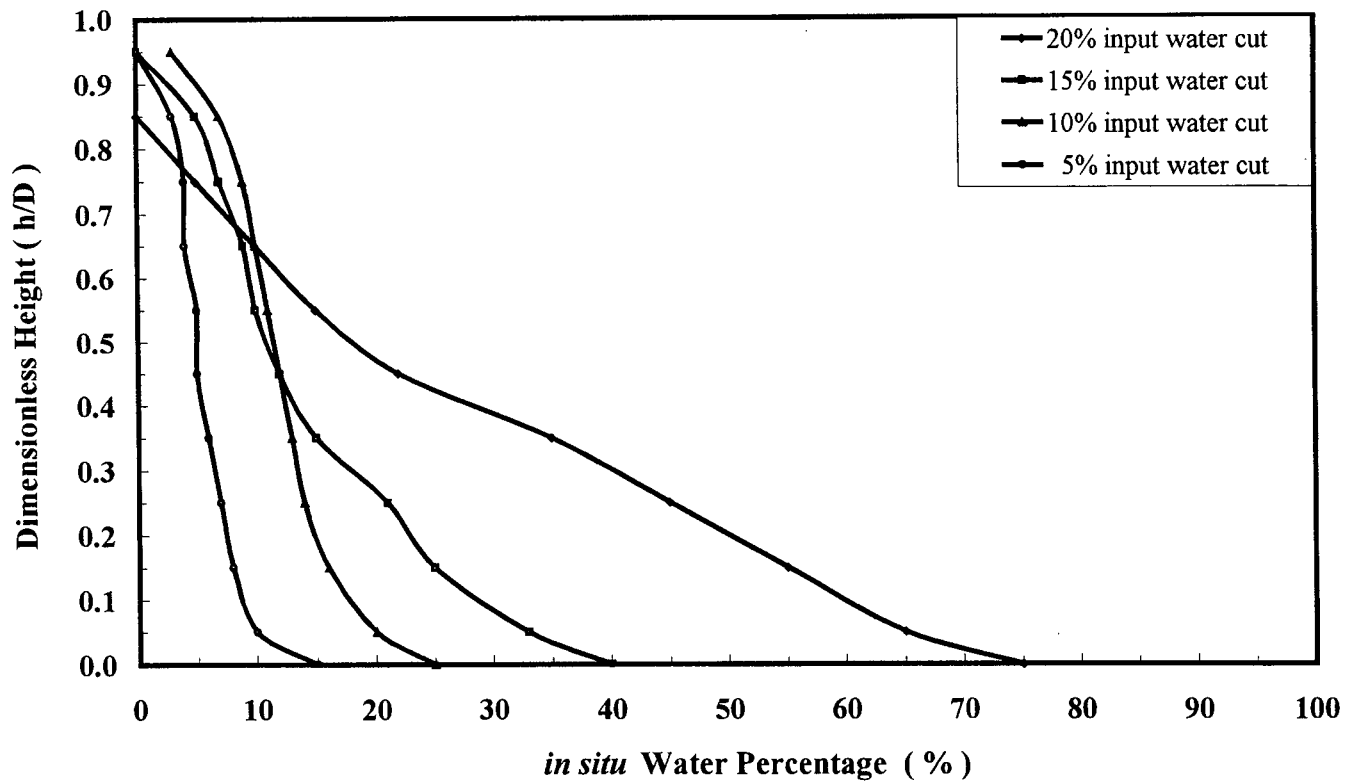**(0.8 m/s, 0 ppm surfactant)**

**Figure 4 Variation of Water Percentage with Vertical Position
(1.2 m/s, 0 ppm surfactant)**

Figure 5 Variation of Water Percentage with Vertical Position
**(1.6 m/s, 0 ppm surfactant)**

Figure 6 Variation of Water Percentage with Vertical Position
(2.0 m/s, 0 ppm surfactant)
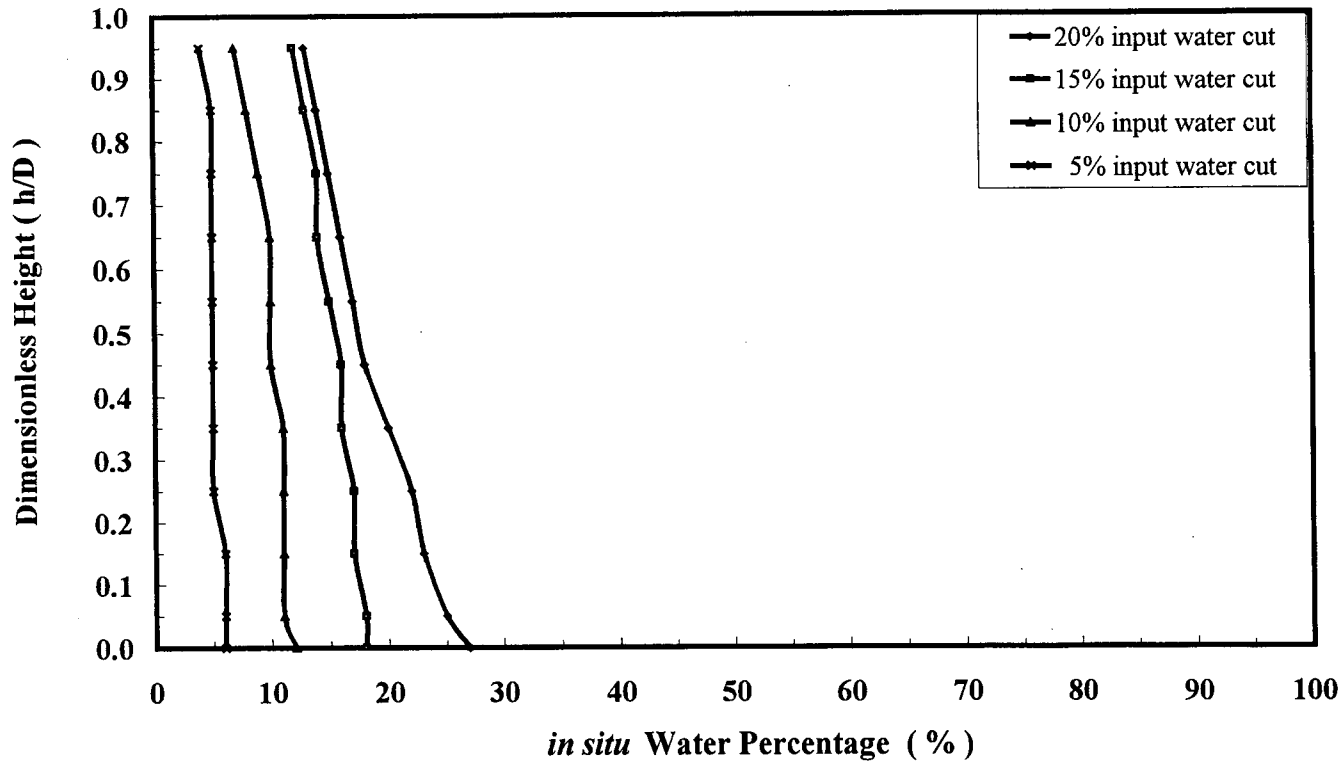
Figure 7 Variation of Water Percentage with Vertical Position
(3.0 m/s, 0 ppm surfactant)
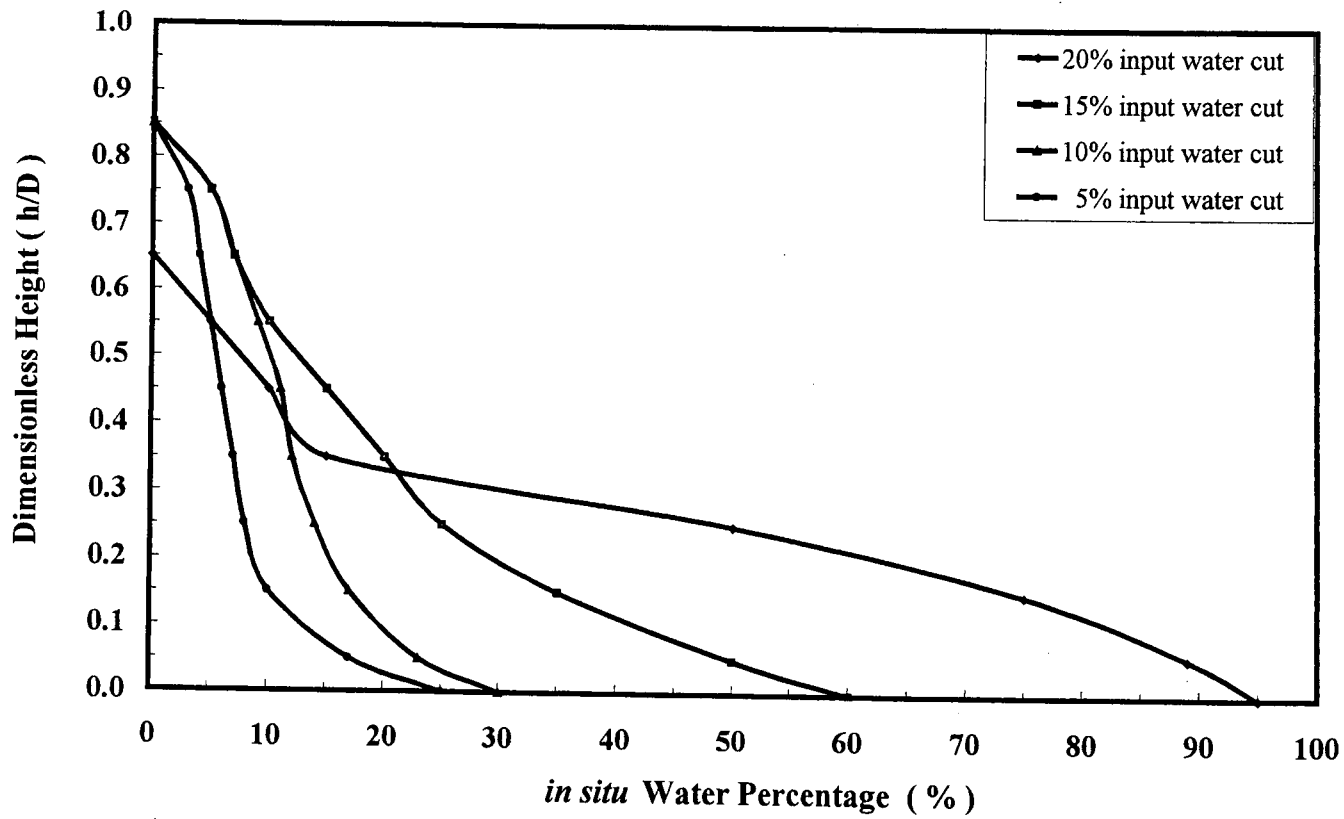
Figure 8 Variation of Water Percentage with Vertical Position
(1.2 m/s, 10ppm surfactant)

Figure 9 Variation of Water Percentage with Vertical Position
(1.6 m/s, 10 ppm surfactant)
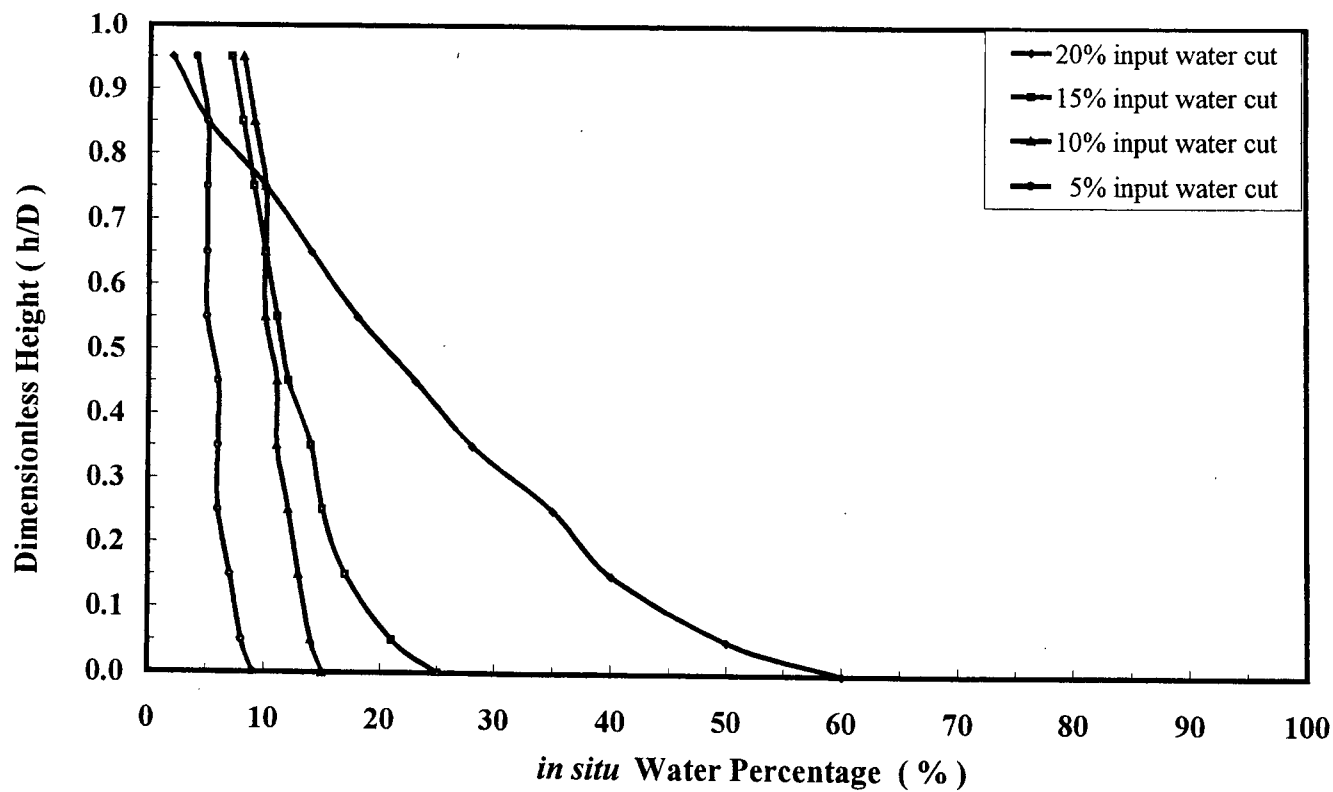
Figure 10 Variation of Water Percentage with Vertical Position
(2.0 m/s, 10 ppm surfactant)
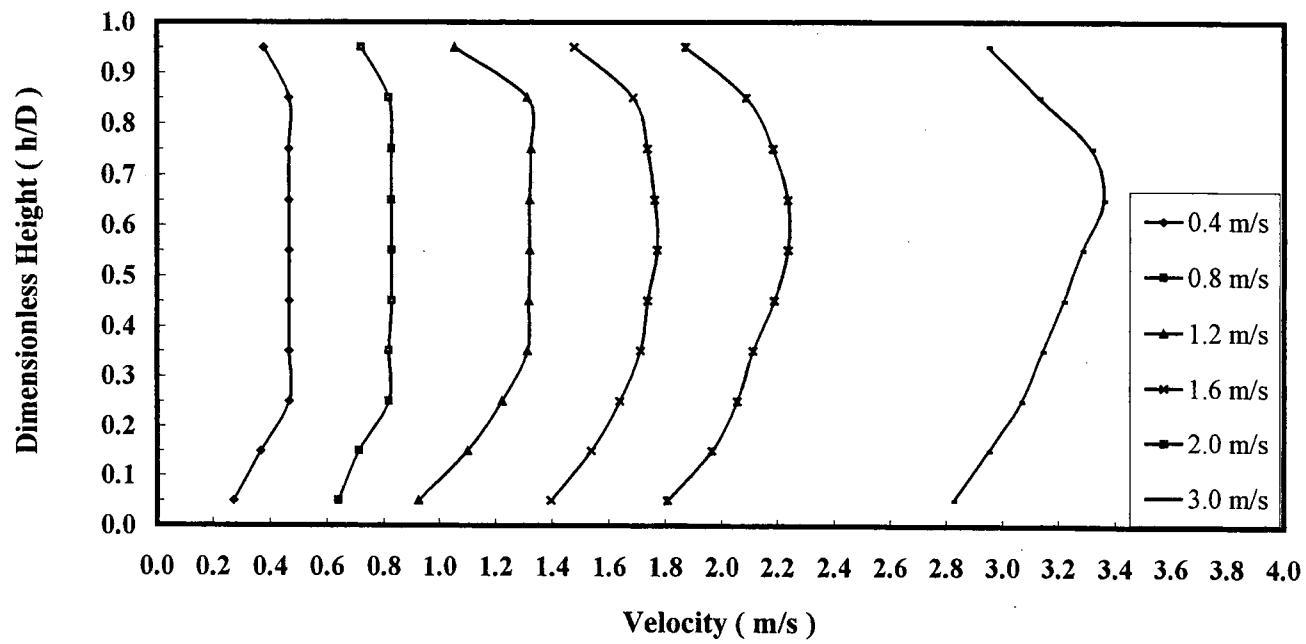
Figure 11 Oil-Water Velocity Profiles (5% input water cut, 0 ppm)
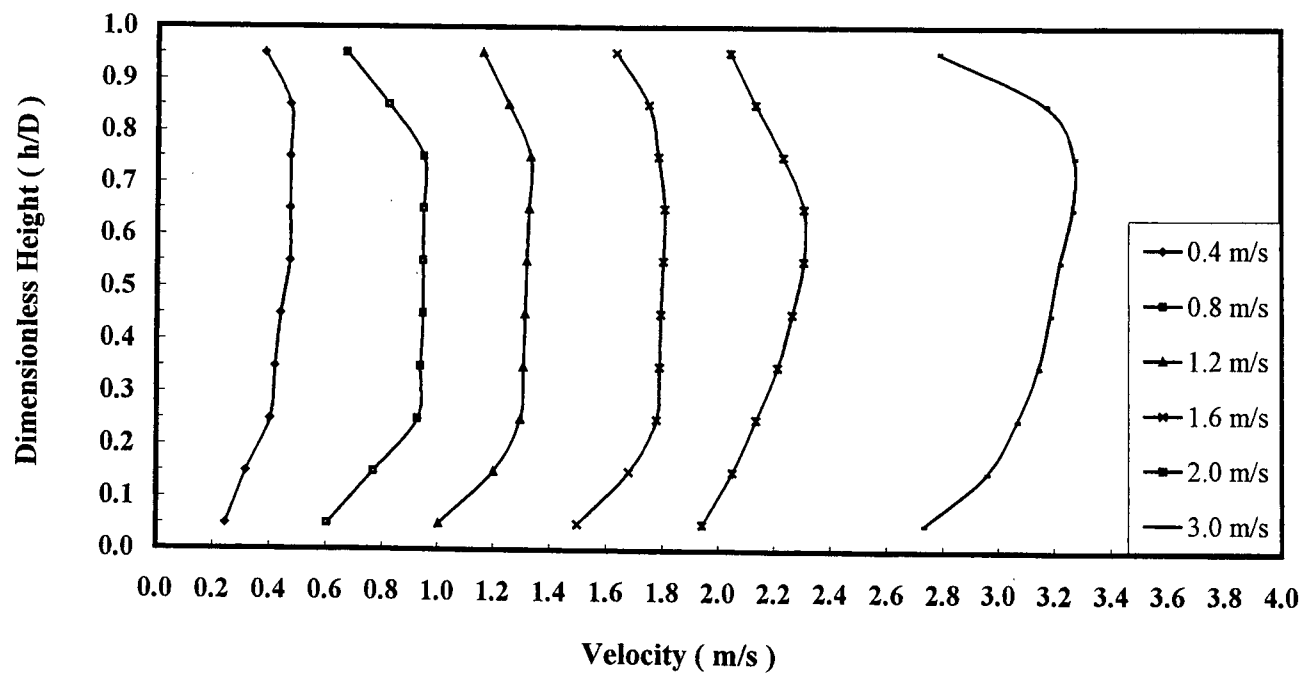
Figure 12 Oil-Water Velocity Profiles (10% input water cut, 0 ppm)
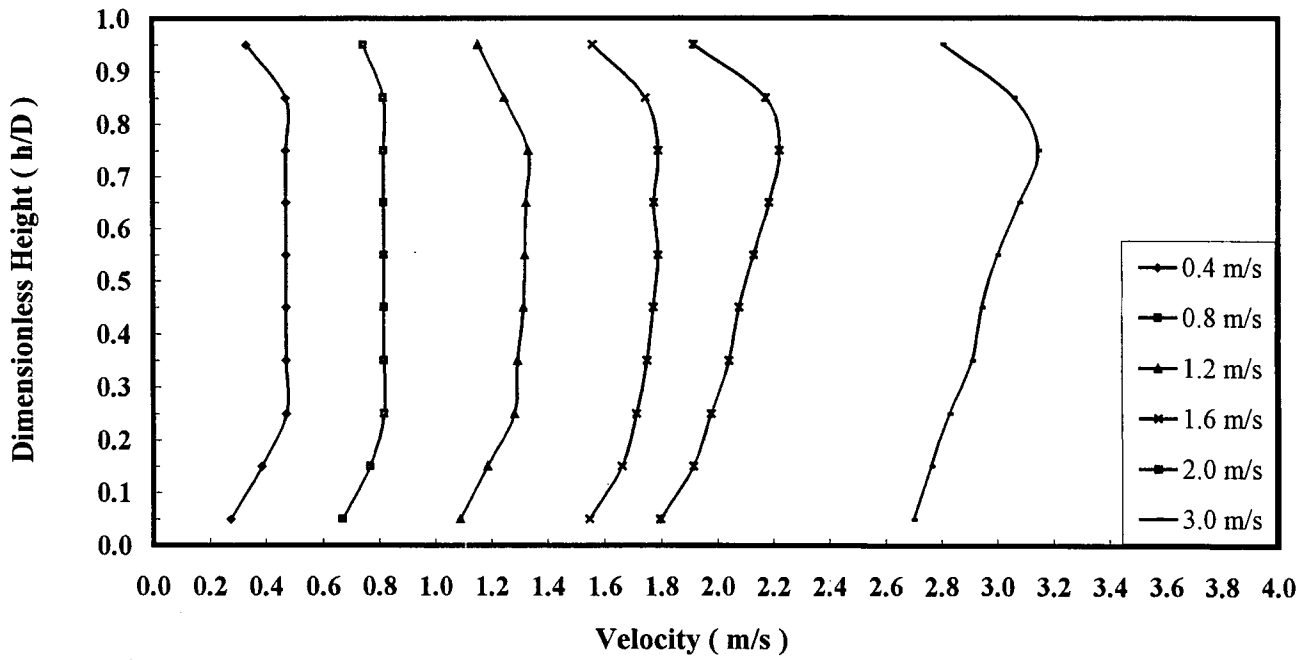
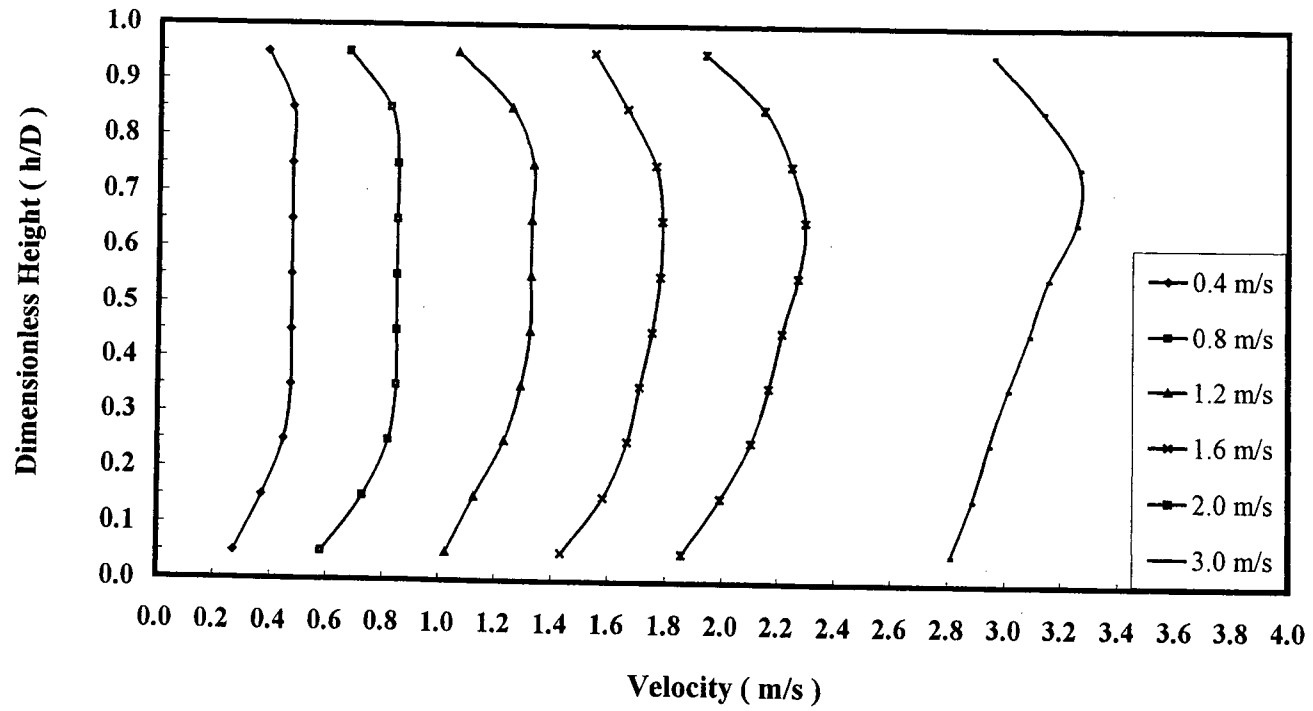**Figure 13 Oil-Water Velocity Profiles (15% input water cut, 0 ppm)**

Figure 14 Oil-Water Velocity Profiles (5% input water cut, 10 ppm)
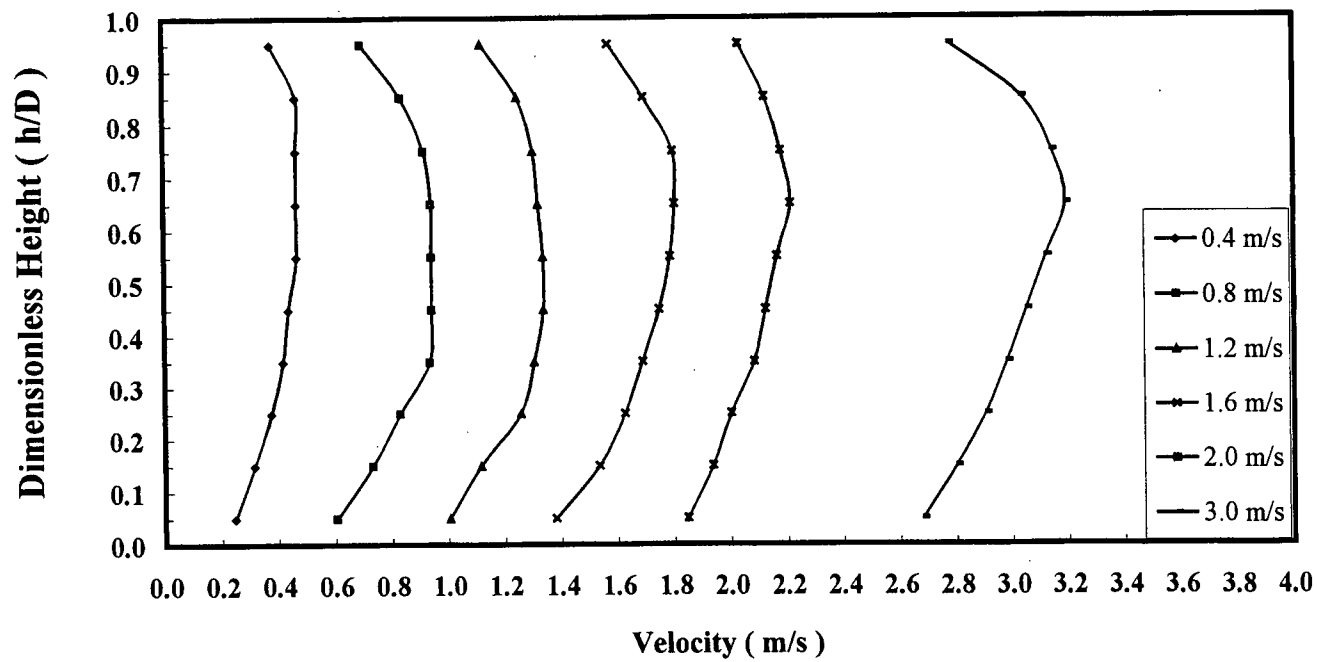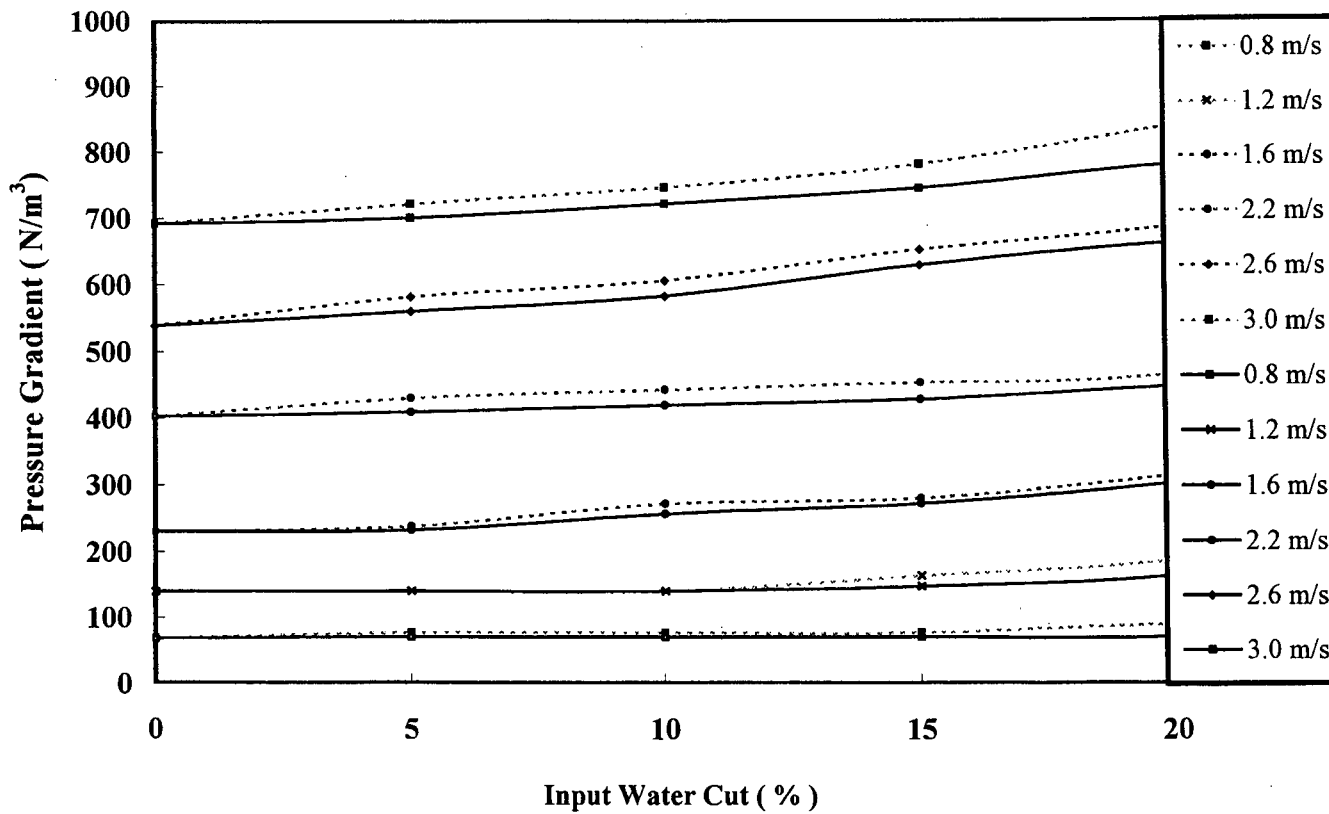
Figure 15 Oil-Water Velocity Profiles (10% input water cut, 10 ppm)

Figure 16 Effect of Surfactant on Pressure Gradient