

DETERMINATION OF PHASE WETTING IN OIL–WATER PIPE FLOWS

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ABSTRACT

Oil-water two-phase flow often presents a internal corrosion problem in pipeline transportation. The corrosion rate of the mild steel line is closely related to which phase wets the pipe wall. The problem has been investigated here on a large scale, in a 60 meter-long flow loop with crude oils. In this paper extensive experimental studies of flow pattern as well as phase wetting determination have been carried out for different crude oils and different pipe inclinations. Four experimental techniques have been applied to determine which phase, water or oil, wets the pipe inner wall at different flowing conditions: wall conductance probes, wall sampling, flow visualization, and corrosion monitoring by electric resistance probes.

Based on the overlapping information from these techniques, comprehensive phase wetting maps for different crudes as a function of water cut and flow velocities were obtained. Three main flow patterns were observed: stratified flow, stratified flow with mixed layer, and dispersed flows. The comparison of flow pattern and wetting regimes gives good understanding of the water wetting mechanism. Moreover, the phase wetting maps produced are a precious tool which can be used as a useful reference for corrosion engineers and pipeline operators to manipulate oil-water two-phase flow systems under corrosion free conditions.

Keywords: CO₂ corrosion, dispersed flow, multiphase flow, stratified flow, water wetting

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INTRODUCTION

The simultaneous flow of two immiscible liquids in pipes, such as oil and water, is a common occurrence in the petroleum industry. A significant amount of water is often present with oil from the well perforations to the final stage of oil separation. The water phase contains dissolved corrosive gases such as CO₂ or H₂S, therefore the water is corrosive. At low water volume fraction, the water is entrained by the flowing oil, consequently oil wets the pipe and the corrosion is negligible. As the volume fraction of water increases, the water “break out” may appear, the bottom of the pipe is wetted by water, and corrosion occurs.

The first notable research on water wetting in oil-water two phase flows was published in 1975 by Wicks and Fraser¹. They proposed a simple model for predicting the critical velocity of the flowing oil phase required to sweep out settled water. However this model was suitable for low water volume fraction. The model underestimates the critical velocity for high water cuts.

Since then, many researchers have taken on the challenge to determine more precisely the flow conditions that lead to water entrainment by the flowing oil. In 1987 Smith *et al.*² pointed out that the oil can carry up to 20% water at velocities larger than 1 ms⁻¹. In 1993, based on the original experiments of Wicks and Fraser, de Waard and Lotz³ declared a binary predicting factor suggesting that oil wetting occurred only for a water volume fraction lower than 30% and velocities larger than 1ms⁻¹. The same year, Adams *et al.*⁴ estimated that below 30% water cut only oil wetting occurs, from 30% to 50% intermittent oil-water wetting exists and at over 50% only water wetting is possible.

The field experience shows that these results are approximate; in some case corrosion (i.e. water wetting) was obtained at water cut as low as 2%. In others conditions, no corrosion (therefore oil wetting) was obtained for water cuts as high as 50%.

As a part of Ohio University’s software package MULTICORP V3.0*^{5,6} a mechanistic model of phase wetting prediction is included. This model calculates the critical velocity of the flowing oil phase required for water entrainment, which is a function of the pipe diameter, pipe inclination, oil density, viscosity, surface tension and temperature. In order to validate this model⁷, a series of experimental studies has been conducted since 2004. These experiments were done in a large diameter fully inclinable flow loop.

EXPERIMENTAL SETUP

Flow loop

All the experiments are conducted in a 25 m long; 10 cm (4 inch) diameter fully inclinable flow loop. The flow loop is specially designed for phase wetting determination in 2 phase or 3 phase flow. Figure 1 shows the schematic of the flow loop⁸.

Oil is stored in a 1.2 m³ stainless steel tank and pumped by a positive displacement pump equipped with a variable speed motor. The oil velocity is precisely controlled in a range of 0.5 - 3 ms⁻¹. Water is stored separately from the oil in another 1.2 m³ stainless steel tank. 1 %wt

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sodium chloride is added to the water phase in order to increase the conductivity of the water. Two positive displacement pumps enabling both low and high flow rates are used to pump the water through the system.

The oil-water mixture is created in a static T-mixer, then flows into a 3 m flexible hose, and into a 14 m straight stainless steel pipe where the flow pattern develops and stabilizes. The mixture then flows through a 2 m long “upstream” test section and a 2 m long transparent pipe, which allows flow visualization. After flowing through two consecutive 90° bends, the mixture goes into a 14 m straight stainless steel pipe where the downstream flow pattern develops and is fully established. The stainless steel pipe section is followed by another 2 m long mild steel “downstream” test section and 2 m long transparent pipe, before entering an oil-water separator.

The separator is a cylinder made of carbon steel (0.8 m internal diameter, 4.8 m long). The internal surface of the separator is carefully coated with corrosion resistant epoxy. Separation efficiency was checked during each test, and was close to 100%. Therefore the separated oil goes into the oil tank and the water flows into the water tank. A good separation is needed to control the oil/water ratio of the flow.

It should be noted that in order to minimize the effect of oxygen on corrosion measurements, the system is deoxygenated before each experiment using pure carbon dioxide. The final oxygen concentration is lower than 25 ppb. Also, particular attention was given to the materials used in the flow loop. The flow loop (except the 2 test sections) is free from corrosion, by using non-corrosive materials such as stainless steel, epoxy, or plastic.

Test section and instrumentation

The test section is a 2 m long carbon steel pipe spool. During the experiments the inner wall of the test section corrodes, which leads to an increase of Fe^{2+} ion concentration by CO_2 corrosion. The general corrosion rate is measured by following the increase of Fe^{2+} ion concentration. Five rows of wall conductance probe, four high frequency impedance probes, one wall sampling port, and an electrical-resistance (ER) probe are installed on the test section as shown in Figure 2.

Instrumentation: Five rows of conductance “pinhead” elements, with a total of 180, form the *wall conductance probe*. It is used to determine the phase wetting along the circumference of the pipe internal wall. Each probe is flush mounted on the pipe wall. A staggered configuration of wall conductance probes is used to minimize the effect of a particular liquid phase “snaking” around the isolated pinheads leading to erroneous readings. In addition, this special configuration is very useful to determine the phase wetting at the flowing condition where small droplets randomly impinge the pipe wall surface.

A *wall sampling port* is used to measure the water/oil ratio close to the pipe surface by extracting the fluid from the bottom of the pipe. It is used to confirm the results of the wall conductance probe. Particular attention was made to avoid erroneous readings by too slow or too fast suction.

An *ER probe* is used to determine the corrosion rate and indirectly the phase wetting condition. The ER probe is mounted on the bottom of the pipe. Corrosion measurements were used to confirm the results obtained by the wall sampling and wall conductance probes.

Finally, the test section is followed by a 2 m long *transparent PVC pipe*, which allows the visualization of the multiphase flow. Visual observation and recording was conducted only for the clear model oil. With real crude oils, flow pattern visual observation is impossible. The overlapping of these four different techniques allows a high degree of confidence in the results described below.

RESULTS

Two main test series of experiments were conducted by using two different oil types. The first series utilized model oil which is transparent and enables the visualization and the understanding of the flow pattern. Phase wetting determination and recording of the flow were carried out. The second series of wetting test experiments was done with a Saudi Arabian crude oil API 39 crude oil. The oils properties are shown in the Table 1 below. Main test parameters are shown in Table 2.

Table 1: Oil properties

		Model Oil	Crude Oil
Density	($\text{kg}\cdot\text{m}^{-3}$)	825	830
Viscosity	(cP)	2.0	4.7
Surface Tension	($\text{dyne}\cdot\text{cm}^{-1}$)	30.0	28.1
Oil-water interfacial tension	($\text{dyne}\cdot\text{cm}^{-1}$)	38.4	26.2

Table 2: Main test parameters

Oil phase	Model Oil	Crude Oil
Water phase	Water + 1% sodium chloride	
Superficial water velocity	0.5 to 3.0 $\text{m}\cdot\text{s}^{-1}$	
Water cut	0 to 20 %	
Pipe diameter	10.2 cm (4 inch)	
Pipe inclination	Horizontal (0°)	0° to $\pm 90^\circ$
Temperature	25 $^\circ\text{C}$	
Pressure	0.13 MPa	

Flow pattern and phase wetting determination

Phase wetting maps were determined based on the overlapping information from wall conductance probe, wall sampling port, corrosion monitoring (Fe^{2+} monitoring & ER probe), and flow visualization. Each phase wetting map shows the wetting state as a function of the oil-water mixture velocity and water cut.

Model oil test: flow pattern and phase wetting map

The results of the wetting determination test obtained with the wall conductance probe are shown in Figure 3. Three wetting regimes were found: water wetting, intermittent wetting, and oil wetting. Four flow patterns were observed: stratified flow, stratified flows with mixing layer, semi dispersed flows and fully dispersed flow.

Mixture velocity = 0.5 m·s⁻¹: at low velocity, stratified flow prevails.

At water cut lower than 10%, water flows as droplets; the droplets average diameter is 10 mm. Interaction between droplets is very weak at these conditions. The droplets wet the pipe periodically. Therefore the wall conductance probe detects an intermittent oil-water wetting condition.

Stratified flow was found for high water cut. As the water volume fraction increases, the coalescence between droplets increases. Around 10 to 15% water cut, all the individual droplet had disappeared to become a single layer of water, flowing at the bottom of the pipe. 10 % water cut is insufficient to form a continuous water layer on the bottom of the pipe. In such condition the wall conductance probe detects intermittent oil-water wetting.

An increase in the water cut up to 15 % creates a clear stratified flow, with a fully continuous water layer on the bottom. The oil-water interface becomes relatively smooth. In such condition the wall conductance probe detects water wetting.

Mixture velocity = 1 m·s⁻¹: stratified flow with mixing layer prevails.

At 1 m·s⁻¹ the flow turbulence increases the rate of breakup, consequently the size of the water droplets decreases to 5 mm average. For water cut lower than 7 %, the small water droplets are dragged into the oil phase and the big droplets wet the bottom of the pipe. According to the wall conductance probe this is an intermittent oil-water wetting condition.

Increasing the water cut up to 10% creates a continuous water layer, but the turbulence disrupts the oil-water interface. Some water is then dragged into the oil phase, the flow becomes stratified with a mixing layer. This means the flow has enough energy to break the oil-water interface but not enough to maintain the water droplets in the flow. Unexpectedly, the water layer is not continuous. The wall conductance probe detects intermittent oil-water wetting conditions.

The increases of the water cut, more than 15%, creates a thick water layer at the bottom of the pipe. For such water cut the wall conductance probe detects water wetting.

Mixture velocity > 1.5 m·s⁻¹: dispersed flow prevails.

The 1.5 m·s⁻¹ is a critical velocity for this model oil-water two-phase horizontal flow. Only dispersed flow and semi-dispersed flow were found for such velocities; this was the case for any water cut in the range of 0 – 20%. The turbulence created small water droplets. These water droplets are ragged by the flow into the oil phase. However, the distribution of water is not uniform; there is more water at the bottom of the pipe than at the top: it is a semi-dispersed flow. According to the wall conductance probe, this is an oil wetting condition.

For higher velocity, more than 2.5 m·s⁻¹, the water is uniformly distributed in the pipe cross section. The oil flow has enough energy to break the oil-water interface and enough

turbulence to sustain the water droplet in the flow; it is a fully dispersed flow. From a corrosion point of view, it is a good situation; the water is maintained kept off the walls of the pipe. Oil wets the entire pipe wall section therefore the pipe is free from corrosion. There is agreement with the corrosion measurement results. Oil wetting is detected by the wall conductance probe.

Crude Oil tests: phase wetting maps at different inclination

The phase wetting results below were obtained by the wall conductance probes. Confirmation is made by wall sampling and corrosion measurement (ER probe & Fe²⁺ monitoring). It should be noticed that crude oil is black, therefore flow visualization is impossible.

Crude Oil horizontal test: water wetting, intermittent wetting, and oil wetting were found.

Figure 4 is a phase wetting map showing the results obtained for the crude oil in horizontal pipe flow. For water cuts higher than 10 % and mixture velocities lower than 1 m·s⁻¹, water wets the pipe. On the contrary, oil wets the pipe for oil-water mixture velocity higher than 1.3m·s⁻¹. In the model oil horizontal test, intermittent oil-water wetting is predominant. In the crude oil test, intermittent oil-water wetting is just a slight transition between water wetting and oil wetting. It should be noticed that the straight line in Figure 4 represents the limit between intermittent oil-water wetting and oil wetting, which is the same as the limit between corrosive and non-corrosive situations.

Crude Oil 5° inclination test: only intermittent wetting and oil wetting were found.

The results of the wetting experiments with crude oil in a 5° inclination upstream flow are shown on Figure 5. Only two different wetting regimes were found with this pipe inclination: intermittent wetting and oil wetting. At velocities lower than 0.8 m·s⁻¹ intermittent oil-water wetting prevails. On the contrary oil wetting is detected for velocities higher than 1.2 m·s⁻¹.

The transition line between corrosive and non-corrosive situations is greatly changed between horizontal pipe flow and 5° upstream flow. The critical velocity to entrain water at 5° flow inclination is approximately 0.3 m·s⁻¹ smaller than for horizontal flow. It is in good agreement with the study by Cai *et al.*⁸ on the effect of slightly inclined oil-water flows.

Crude Oil 45° inclination: intermittent wetting and oil wetting were found.

Interestingly, as shown in Figure 6, the results of the oil-water wetting test at 45° upward flow are not significantly different from the results obtained at 5°. Continuous water wetting is not found in this condition. As for the 5° inclination test, higher water cut than 15 % and lower oil-water mixture velocities than 0.8 m·s⁻¹ correspond to intermittent oil-water wetting. On the contrary at high velocity (>1 m·s⁻¹) only oil wetting occurs.

The transition lines between the corrosive and non-corrosive environments as depicted in Figure 5 and Figure 6 overlap. Consequently, the gravity effect on the oil-water two phase flows is not very different between 5° and 45° inclination when it comes to the phase wetting conditions.

Crude Oil 90° inclination: intermittent wetting and oil wetting were found.

Figure 7 shows the phase wetting map of crude oil in 90° upward inclined pipe flow. As for 45° inclination, steady water wetting is not found. The intermittent oil-water wetting is found

for the same conditions: water cut higher than 15 % and oil-water mixture velocity lower than $0.7 \text{ m}\cdot\text{s}^{-1}$. The oil wetting occurs at oil-water mixture velocity greater than $1 \text{ m}\cdot\text{s}^{-1}$.

The oil-water two phase flow test at 90° inclination are slightly different from the 45° inclination test: transition lines are parallel and the intercepts are only $0.1 \text{ m}\cdot\text{s}^{-1}$ different.

Discussion

Effect of the flow on the wetting phase: Model Oil

During the test of the model oil, four different flow behaviors were found: stratified flow, stratified flow with mixing layer, semi dispersed flow and fully dispersed flow. Figure 8 is a representation of the model oil-water two phase flow pattern map. There is a perfect overlapping of the boundaries between stratified flow and dispersed flow in Figure 8; and the limit between intermittent wetting and oil wetting in Figure 3. This is suggesting that the flow pattern has a significant effect on which phase, either oil or water, wets the pipe.

Stratified flow: water flows on the bottom of the pipe; consequently, the water wets the pipe.

Stratified flow was found for low velocity ($<1 \text{ m}\cdot\text{s}^{-1}$) at any water cut used (0 – 20%). Water wetting was found only for water cuts higher than 15% whereas intermittent oil-water wetting was found for lower water cuts. This can be explained by the rate of water droplet coalescence. At low water cut, the water droplets are dispersed on the bottom of the pipe and randomly wet the pipe; it is an intermittent oil-water wetting situation. As the water cut increases the rate of coalescence between water droplets increases too. Around 15% water cut, there is enough water to create a continuous water layer. The water wets the bottom of the pipe continuously, leading to a steady water wetting condition.

Stratified flow with mixing layer: water flows on the bottom of the pipe; consequently, the water wets the pipe.

In the range 0 to 15% water cut and 1 to $1.5 \text{ m}\cdot\text{s}^{-1}$ velocities, only intermittent oil-water wetting was found. The water layer formed is not continuous allowing the oil to wet the bottom of the pipe for short periods of time. At $1 \text{ m}\cdot\text{s}^{-1}$ mixture velocity the water pump could not deliver more than 15% of the total flow rate, but presumably for higher water cut a continuous water layer would be formed.

Semi-dispersed flow: Water droplets are flowing in the oil phase and oil wets the whole pipe wall.

Semi-dispersed flow was found for high velocity, more than $1.5 \text{ m}\cdot\text{s}^{-1}$. At such velocity the turbulence breaks the oil-water interface. Consequently, water flows as small droplets entrained by the oil phase. However, if the distribution of water is not uniform, more water droplets can be seen in the bottom portion of the pipe. Oil wets all the pipe sections, this is an oil wetting situation.

Dispersed flow: Water droplets are dispersed in the oil flow and oil wets the whole pipe wall.

At oil-water mixture velocities higher than $2.5 \text{ m}\cdot\text{s}^{-1}$, the water droplets are small and their distribution in the pipe cross section is apparently uniform. It appears that all the water phase is fully entrained by the flowing oil phase, which is an oil wetting situation.

Effect of the pipe inclination: Crude Oil

Figure 4, Figure 5, Figure 6 and Figure 7 transition lines are shown together in Figure 9. This figure shows the transition line between corrosive and non corrosive situation for the crude oil wetting test at different pipeline inclination: horizontal, 5°, 45° and 90°. With the increase of the inclination, the transition line is shifted to a lower oil-water mixture velocity. Consequently, the water wetting domain shrinks with the pipe inclination. This phenomenon can be explained: the water wetting area corresponds to the stratified flow when the water flows on the bottom and steadily wets the bottom of the pipe. Stratified flow is formed when the gravity force (separation oil-water) is stronger than the turbulence (mixing), and the gravity force effect depends on the pipe inclination whereas the turbulence does not. The relevant component of the gravity force normal to the flow direction is lowered by increasing the inclination. Horizontal flow is the easiest configuration to obtain stratified flow and steady water wetting. On the other hand, vertical flows can not sustain stratified flow.

On Figure 9 the transition line for 5° inclination is somewhat unexpected. This line represents the limiting velocity between intermittent wetting and oil wetting. This line changed more between horizontal and 5° inclination flows than between 5° and 90° inclination. The overlapping of the transition line between 5°, 45°, and 90° shows that the effect of the pipe inclination is more important at slight inclinations than for high inclinations.

CONCLUSION

In this study two types of oil: model oil and crude oil, have been used in large scale phase wetting tests. Four experimental techniques (wall conductance probes, wall sampling, flow visualization and corrosion monitoring) have been applied to determine which phase (either water or oil) wets the pipe inner wall at different flow conditions. Based on the overlapping information from these techniques, comprehensive phase wetting maps were obtained. Four flow patterns were observed: stratified flow, stratified flow with mixed layer, semi-dispersed flow and dispersed flow. These results enable us to predict the flow conditions which lead to a understanding of the wetting phase in oil-water two-phase flow. On the other hand, this study will provide useful information for engineers on how to model and design crude oil transportation pipelines and operate these systems under corrosion-free flowing conditions.

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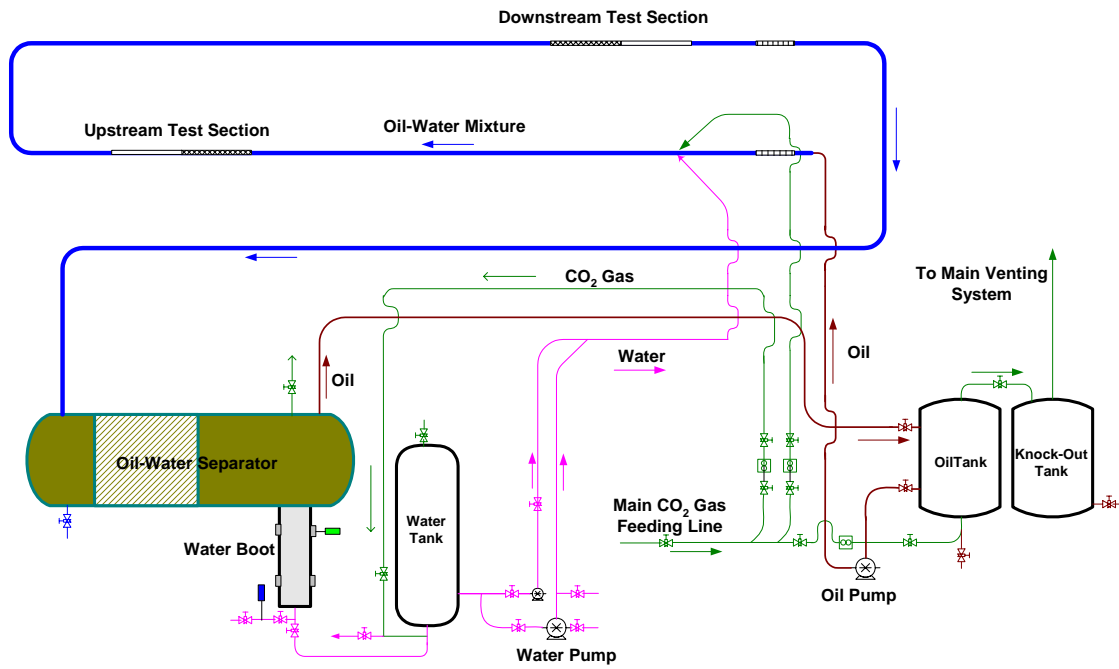


Figure 1: Schematic of 4-inch I.D. fully inclinable multiphase flow loop

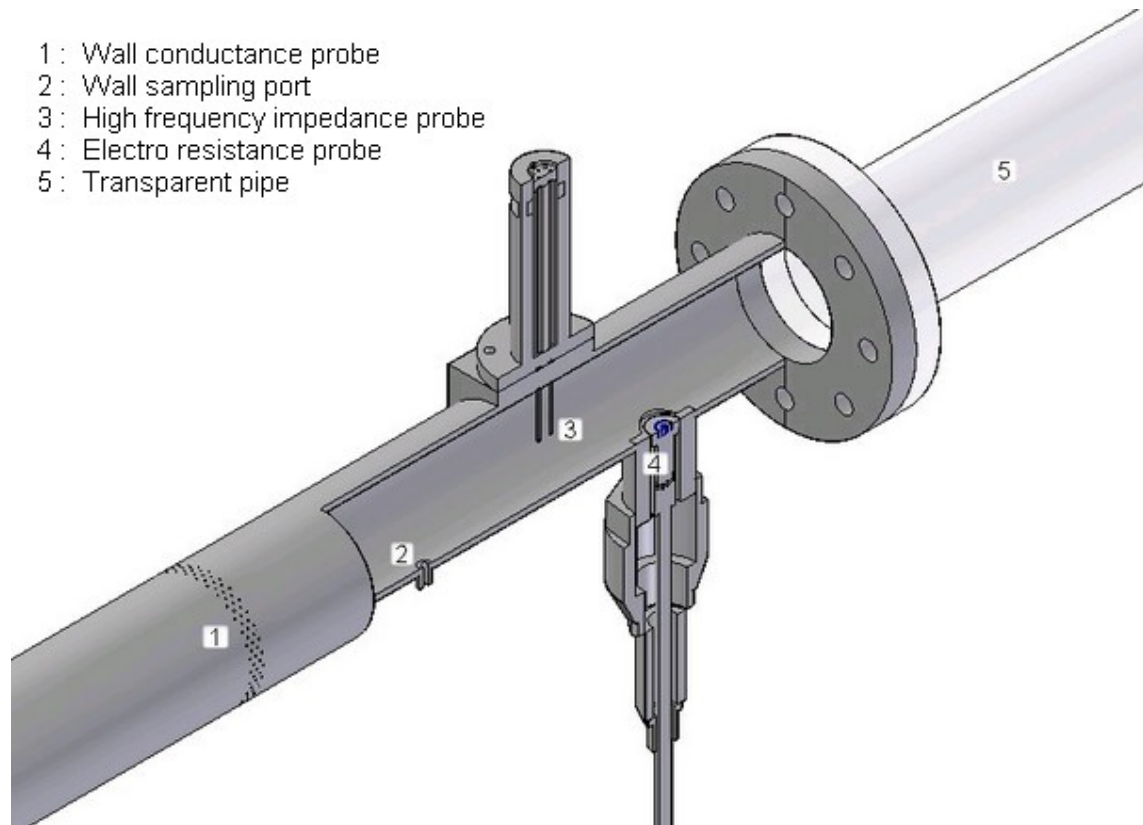


Figure 2: Test section cross section

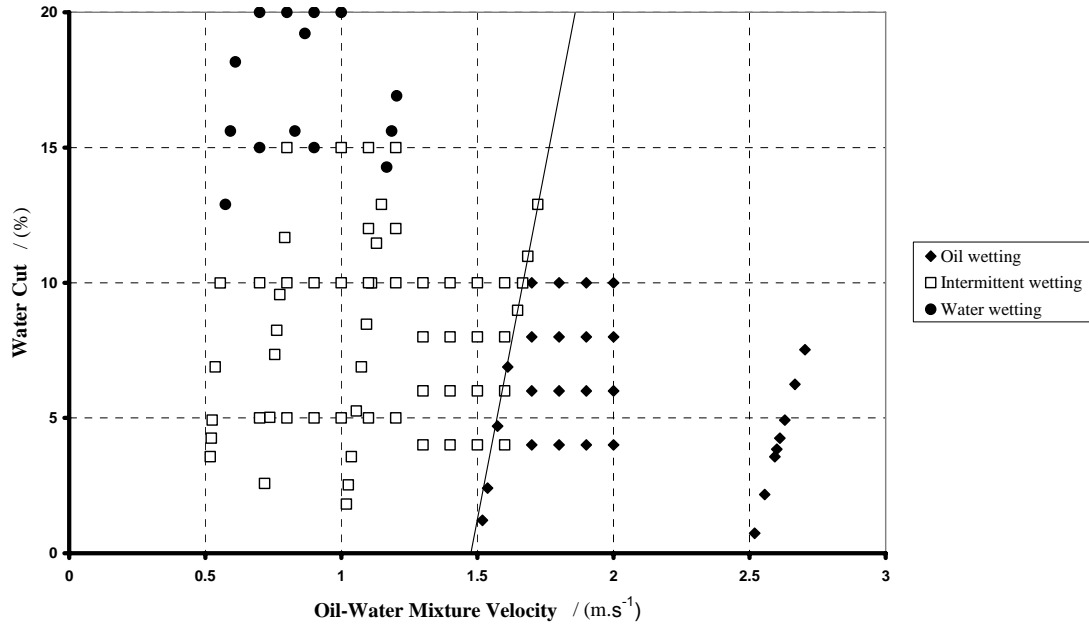


Figure 3: Phase wetting map water-model oil horizontal flow

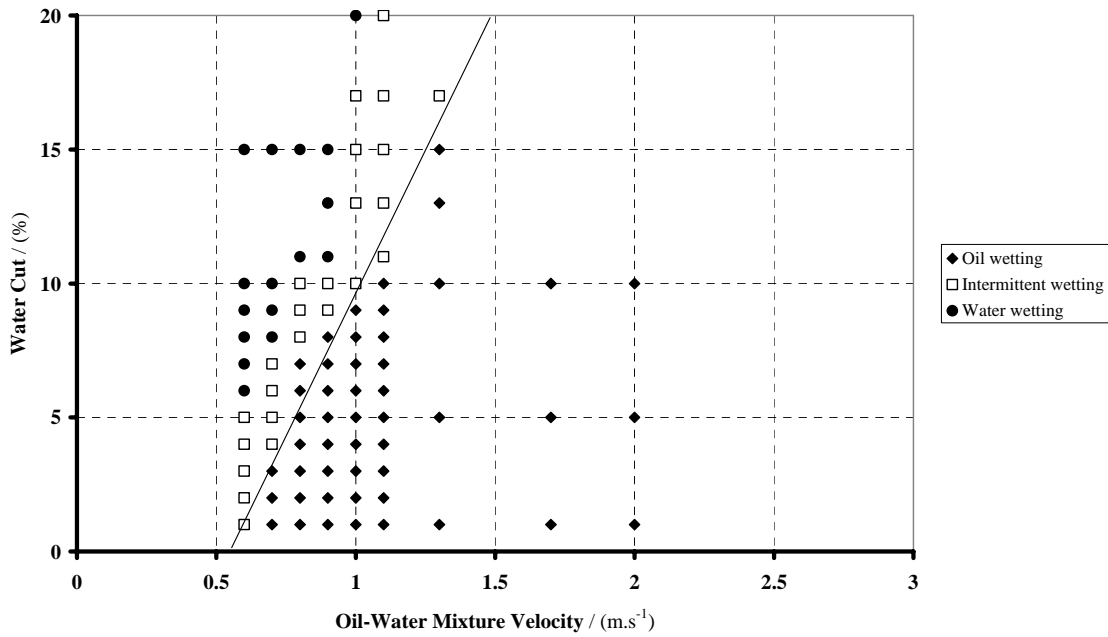


Figure 4: Phase wetting map water- crude oil horizontal flow

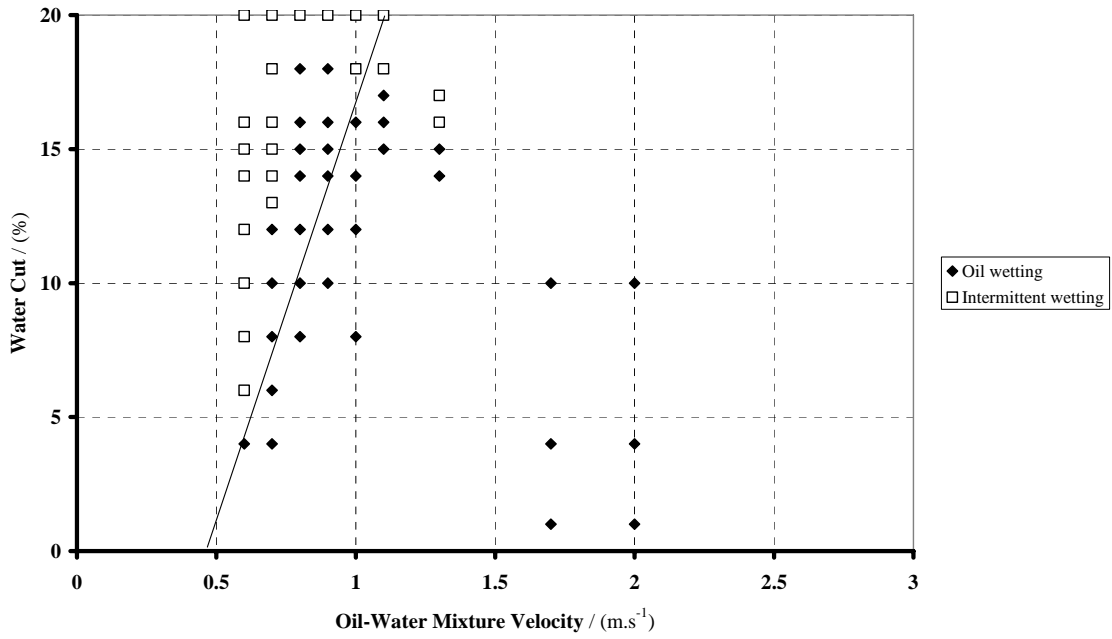


Figure 5: Phase wetting map water- crude oil 5° inclination upward flow

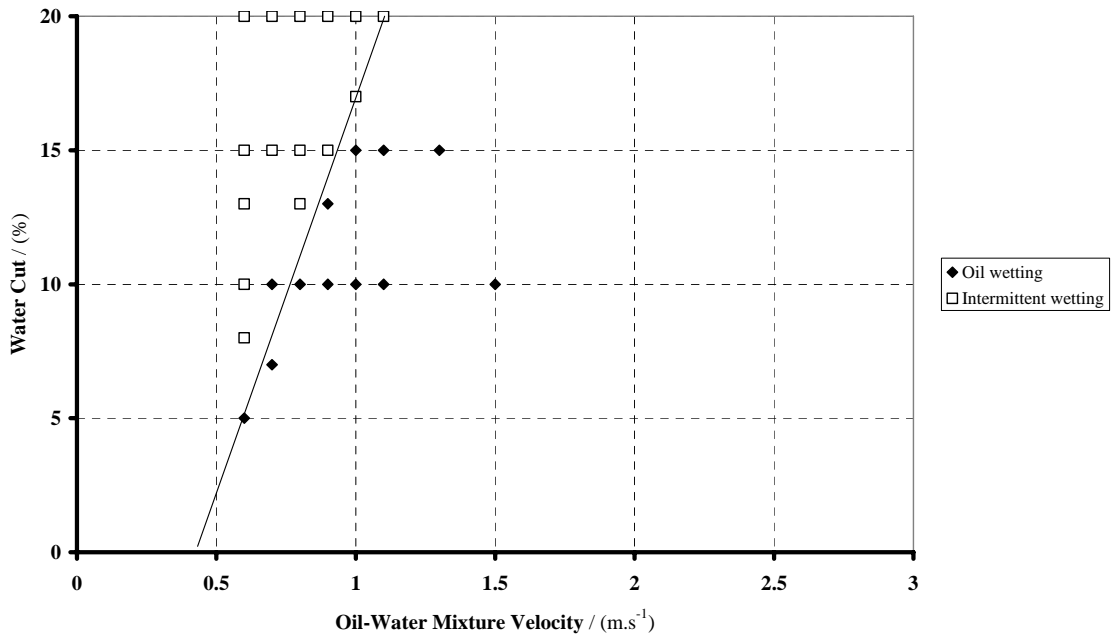


Figure 6: Phase wetting map water- crude oil 45° inclination upward flow

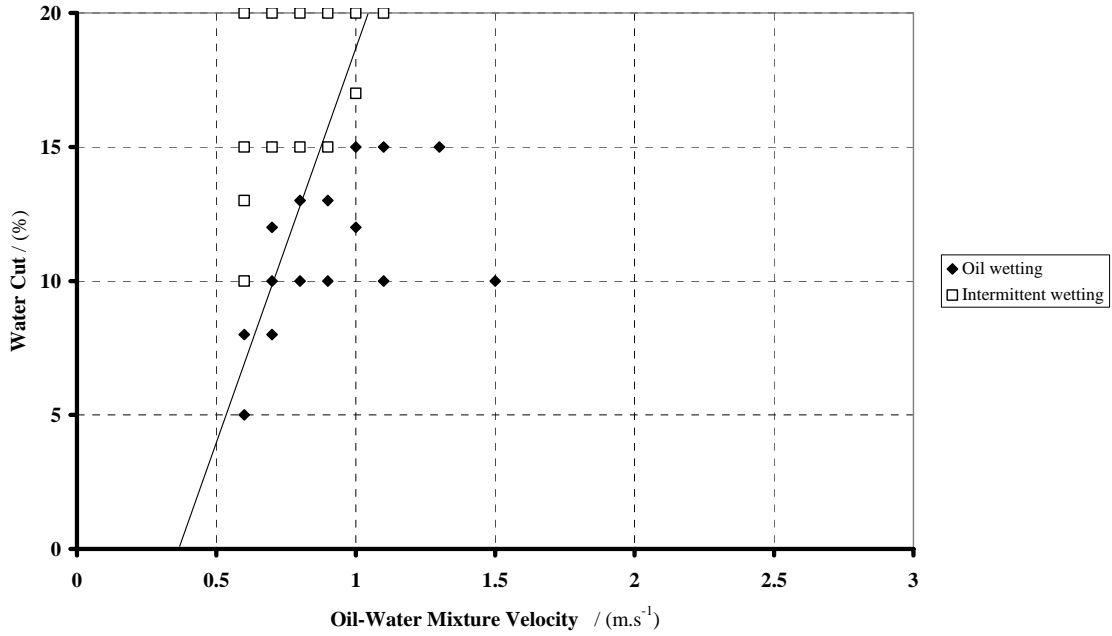


Figure 7: Phase wetting map water- crude oil 90° inclination upward flow

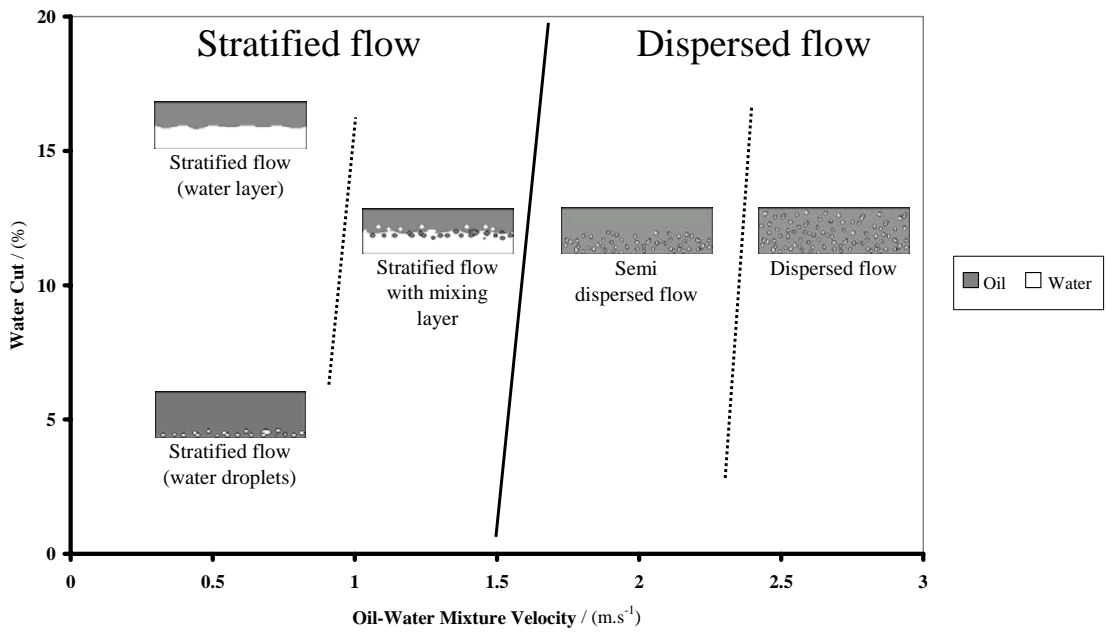


Figure 8: Flow pattern map model oil test

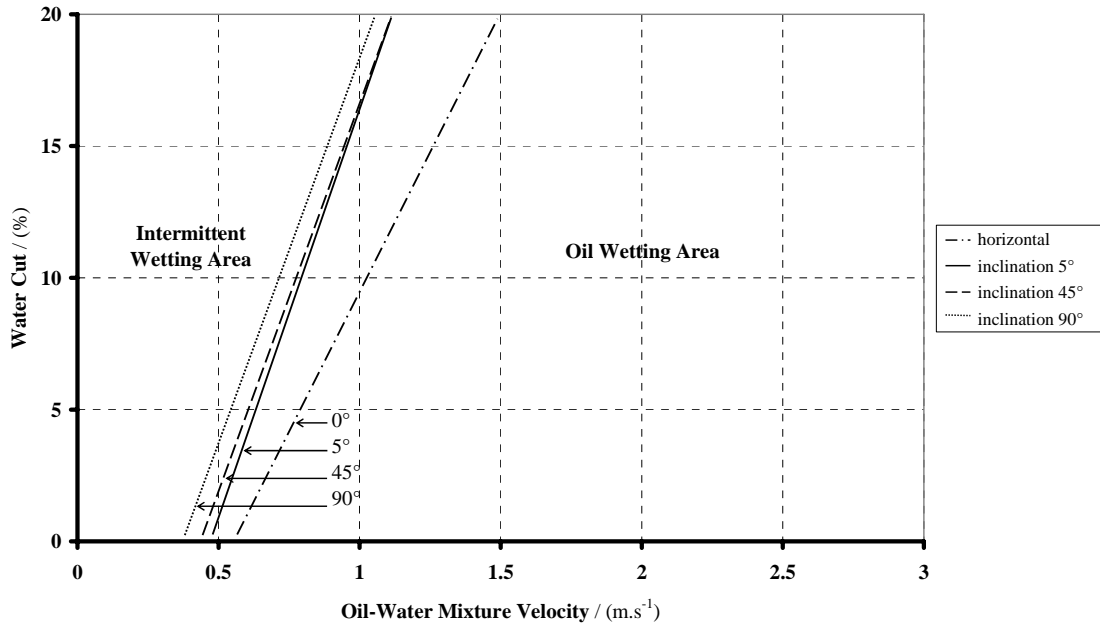


Figure 9: Comparison transition line (corrosive non corrosive situation) for phase wetting map water- crude oil in horizontal, 5°, 45°, and 90° inclination