

Advanced Profile Gauge for Multiphase Systems

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Abstract - A profile gauge, based on the measurement of capacitance of the surrounding medium, is presented. 40 sensors (electrodes) are positioned along a rod. Each sensor uses an oscillator working in the lower 20MHz range. The presence of the surrounding fluid causes a change in frequency depending on the dielectric property of the fluid. This change in frequency is transformed to a volume-averaged value of dielectric constant of the surrounding fluid. Contrary to "normal" types of dielectric measurement techniques the advanced profile gauge does not measure the capacitance between electrodes.

The probe has been tested in an atmospheric system at ambient temperature containing salt water, condensate from the Sleipner field and air. The advanced profile gauge was fitted to a transparent separator with internal diameter of 380mm. The positions of the interfaces could be visually observed, and observations showed that the separator normally had four distinct regions; gas at the top, a condensate layer, an emulsion layer and at the bottom a water phase.

The results show that the measuring system was able to detect the gas/condensate interface and the condensate/emulsion interface within $\pm 20\text{mm}$ in all the tests. With regard to the emulsion/water interface, this was detected within $\pm 20\text{mm}$ in all but four tests.

The accuracy is within $\pm 10\%$ in all the tests. At high levels, the accuracy is $\pm 5\%$. The reason for this is that values are predicted within $\pm 20\text{mm}$ whatever the position of the interface.

Keywords: capacitance, oscillator, interface, separator

1. INTRODUCTION

For a number of years, reliable level measurements have been sought in the process industry. In high-pressure equipment, it is normally not possible to observe the internals of pressure vessels and many different types of level measuring systems have been developed. However, if the process system contains fluids that do not form easily definable interfaces, existing level measuring systems often fail. For example, the use of viewing glasses mounted on a vessel containing complicated fluid layers, foam, emulsions and so forth, must fail since the levels that form in the vertical glass tube in no way represent the conditions inside the vessel.

Instead of level measuring devices, profile gauges try to give more information on the vertical fluid distribution inside vessels.

Detailed knowledge on the phase behaviour inside vessels is valuable. Separators can for example be operated at optimum conditions, positioning the interfaces such that the outlet streams become as clean as possible. In addition, the addition of expensive chemicals, such as de-foamers and de-emulsifiers, can be done

at optimum concentrations. The economic potential is large if separation processes can be controlled with adequate accuracy.

2. LITTERATURE

Capacitive systems have previously been used to measure the positions of interfaces in process vessels, and for recording information for tomographic systems, [1, 2]. These systems normally measure the capacitance between pairs of electrodes, [3]. A common problem has been the presence of water films between the electrodes. Water films introduce severe problems to the probes as the presence of the water "short circuits" the circuit. In certain conditions, even the remains of water films on glass tubes ruin system performance, [4].

High precision capacitive gauges, [5], are available for the measurement of levels in different types of vessels, again measuring between electrodes.

3. THE ADVANCED PROFILE GAUGE

The Advanced Profile Gauge measuring system is based on the measurement of the dielectric constant of the surrounding medium.

The low-pressure probe consists of 40 electrodes (sensors) electrically insulated from the surrounding fluid. Each of the electrodes has its own dedicated electronic circuit with an integrated oscillator. Measurements are done in sequence. In practice, this means that all 40 sensors are read once a second.

3.1 Abbreviations:

oscRT	oscillator reference temperature (normally +23°C)
oscAC	oscillator absolute capacitance
oscACC	oscillator absolute capacitance compensated
oscTC	oscillator temperature coefficient
oscF0	oscillator frequency (approx. 20MHz)
oscTD	oscillator temperature digitised. Oscillator at crude temperature assumed.
oscCC	oscillator capacitance change (due to any oil/water outside window)
oscCCF	oscillator capacitance change factor

3.2 Measuring Principle

The technology is based on well-known principles for measuring capacitance. These principles are, however, highly improved by the new method that improves accuracy (resolution) and repeatability. Patent is applied for the method.

In simple terms, a liquid detection probe consists of several capacitive elements "stacked" on top of each other. Each element can be read individually and gives linear information about the dielectric characteristics of its surroundings. This is an improvement compared to most other probes that only gives binary (on/off) information from each segment.

Another essential element is that the sensor is based on only one surface. This means that there is not necessary for the fluid to flow between two surfaces. This simplifies the mechanical construction of the probe, and at the same time improves the measurement, as there is no need to create artificial flow patterns to make the probe perform.

The following are data for a typical probe in a separator vessel.

3.3 Oscillator circuit

The measuring principle is based on the dielectric value of a medium such as oil/water.

The dielectric constant of crude oil is normally 1.8 -2.5, and for process water from 57 to 85, dependent on the salinity and temperature.

The dielectric constant for oil/water can easily be measured. If the oil/water is part of a capacitor, the capacitance will change according to the surrounding fluid.

If the capacitance is a part of an oscillator, as shown in Figure 1, a change in the capacitance will change the operating frequency of the oscillator, which can be measured with a frequency meter.

The sensitivity of an oscillator in an arrangement like this is very high. The sensitivity of a change in capacitance is in the order of 0.0003pF with a measuring time of 10ms.

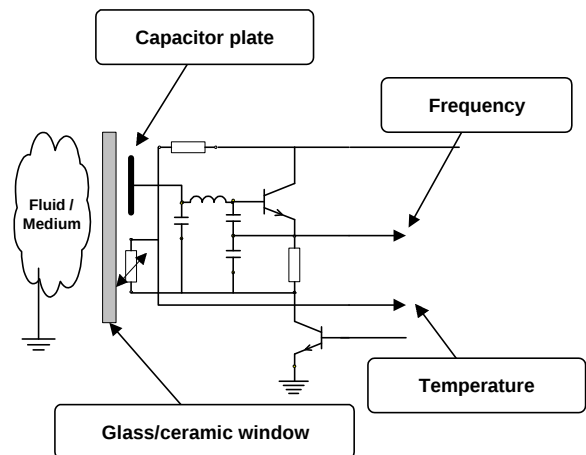


Figure 1: Oscillator and its capacitor plate

The real part that will detect the capacitance is a metal plate forming one part of a capacitor, while the other "plate" is at an infinite distance.

As seen in Figure 1, there is a temperature sensor for each oscillator, that reflects the temperature of the oscillator and the fluid outside the glass /ceramic window.

The temperature is a very vital information, since the oscillator, water and crude oil are temperature dependent.

By stacking several selectable oscillators on top of each other in a rod, as shown in Figure 2, it is possible to measure the fluid profiles in a separator. The scanning of all oscillators is done by a Personal Computer (PC) in such a way that only one oscillator with its temperature sensor is activated at a time.

The distance between oscillators with its capacitor plate is 10mm, giving an average fluid phase selectivity of less than 20mm.

3.4 Calibration of oscillators:

Because the absolute capacitances of the oscillators are not exactly equal, due to small mechanical and electrically differences, all oscillators absolute capacitance is logged in a database.

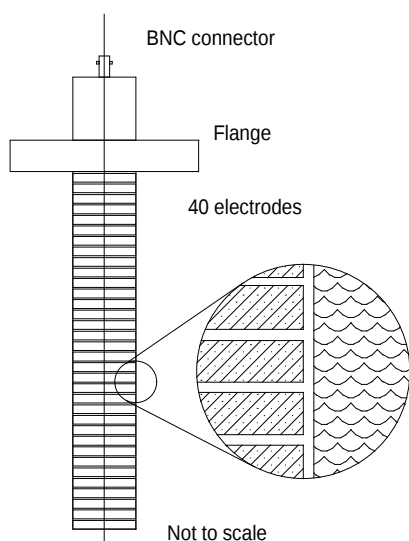


Figure 2: Probe assembly

Phase 1, all oscillators are at the same temperature (+23°C) and in air, and data logged are:

1. Temperature (oscRT)
2. absolute capacitance (oscAC)

Phase 2 is needed to determine the temperature coefficient of the oscillator capacitance (oscTC). So all oscillators are raised to +100°C, and the oscTC are computed for all oscillators and logged to the database:

3. oscTC

Phase 3. Because the capacitance (oscCC) does not change equally when exposed to water/oil on all oscillators, these differences must be logged. This is done by emerging all oscillators in tap water, and this difference is logged as a factor for each oscillator (oscCCF).

These variations are due to small mechanical and electrically differences.

4. oscCCF

These four values are stored in the database for each oscillator.

3.5 Calibration of crude oil:

Since the dielectric value differs from crude to crude, the need to make a database of all the crudes to be used on a selected site is vital.

With a sample of dry crude, the dielectric constant (crudeDC) and its temperature coefficient (crudeTC) are logged in a database:

1. temperature
2. crudeDC
3. crudeTC

A scan of all oscillators will start with addressing oscillator #1, then #2 and so on until the last oscillator is selected.

3.6 Mechanical design

The probe is made as a tube that is mounted vertically into the tank. To be able to measure with the highest accuracy possible, a pipe of a composite material was used as housing for the probe. The electrodes consisted of pieces of copper foil that were glued to the composite surface. The whole assembly was then mounted inside a Perspex cylinder to insulate the electrodes from the surrounding fluid. Each electrode was connected to a print-card that goes the entire length of the probe. This print-card holds all the components. There are no moving parts in the probe.

The tube was filled with potting material (fluoride based silicon), and then sealed.

3.7 Mounting

The probe was mounted vertically through a flange at the top of a transparent separator vessel as shown in Figure 3. The measuring system is certified EXi for operation in explosion hazardous environments. Communication from the probe to the control system employs a single



Figure 3: Photograph of probe mounted in vessel. Each electrode is numbered. An emulsion layer is seen between the condensate layer and the water layer.

coaxial cable. Barrier modules are located in a

safe area where PC and other necessary equipment are located.

Since the separator was transparent, it was possible to observe the electrodes visually. In order to ease the visual observations each electrode was numbered.

4. TEST DESCRIPTION

4.1 Test apparatus

The probe was fitted to a separator that should undertake a series of separation tests on a fluid system containing condensate from the Sleipner field in the North Sea, salt water and air. The separator was operated at a range of different flow rates of the individual phases.

The signals from the probe were monitored on the display of a PC. The probe signals were also logged to file for later analysis or playback. Visual observations of the interfaces within the vessel were recorded in a logbook during the experimental runs. Rulers, graduated in mm, were fitted to the vessel, to ease the visual recordings.

4.2 PC Software

The PC display includes a colour representation of the signal values. It is possible to include an arbitrary number of nodes where the numerical value is assigned a special colour. Values between the nodes are given a colour that results from a blending of the adjacent node colours. Numerical values between defined colours are blended to give a colour representing the intermediate value.

Typically, in these tests water was defined to be blue¹ and exist at values above 950. Pure condensate exhibited a numerical value of approximately 180 and was given the colour yellow. Air was assigned the values below 10 and given the colour white.

This makes it possible to highlight all the gradients in the signal by choosing appropriate node positions.

Two plots were generated, an online plot showing signal values as horizontal bars and a plot showing the variation with time. A sample of the online plot is shown in Figure 4.

The time variation plot can be generated based on the output file. This plot shows the variation with time. It should be emphasised that this plot is just the raw data with colour coding. The gradients that are visualised represent interfaces in the system. The interfaces are obvious to the eye, as shown in Figure 5.

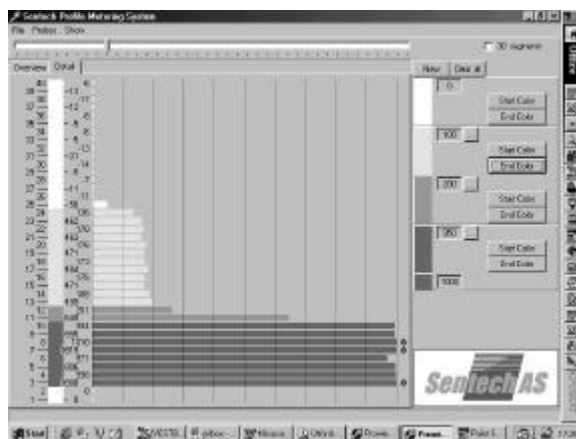


Figure 4: Online plot from probe

5. RESULTS

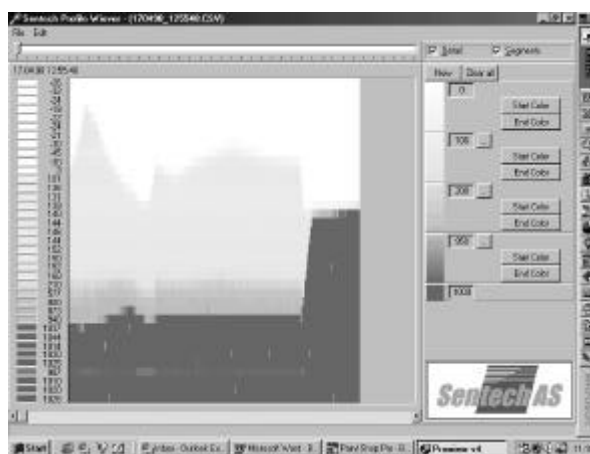


Figure 5: Diagram showing variation with time. Gradients coincide with fluid interfaces.

5.1 Raw data

The raw data show different types of behaviour. In some tests, it is easy to see where the interfaces are located. In another group of tests, the concentration profiles continue into the water zone and the condensate zone. This makes it more difficult to see sharply where the condensate and water layers end. Thirdly, in some tests the gradient in signal value is the same across an interface. This makes it impossible to detect the position of the interface from analysis of the signal versus position curve.

A typical uncalibrated data signal, from test 17a, is shown in Figure 6. If this signal is adjusted by subtracting the base signal the probe measures in air, the adjusted signal in Figure 7 results.

¹ Figure 4 and Figure 5 have been produced in grey-scale for this paper.

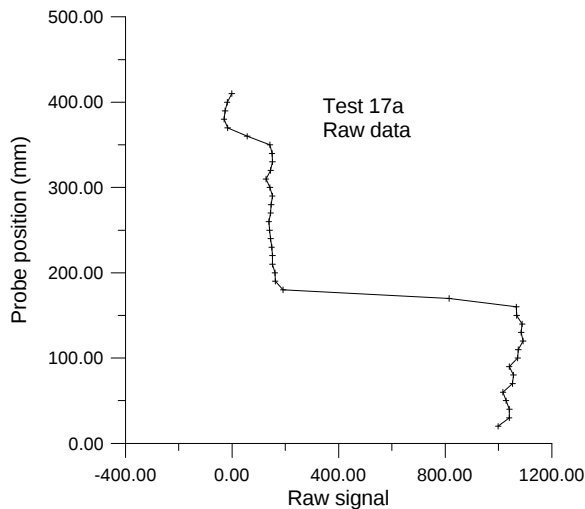


Figure 6: Typical uncalibrated signal versus probe position

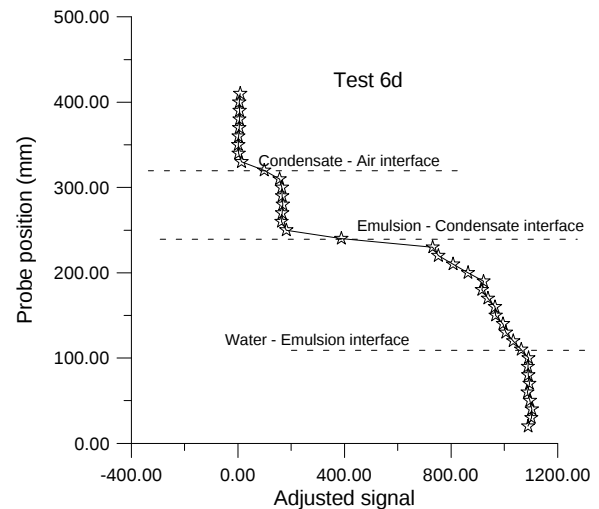


Figure 8: Adjusted signal where interface positions are superimposed.

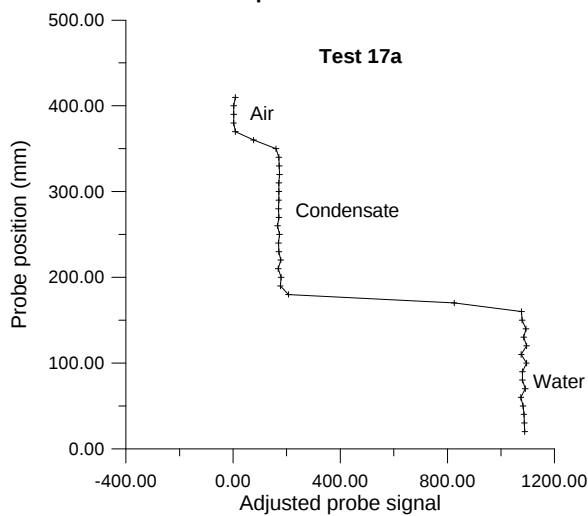


Figure 7: Adjusted signal versus probe position.

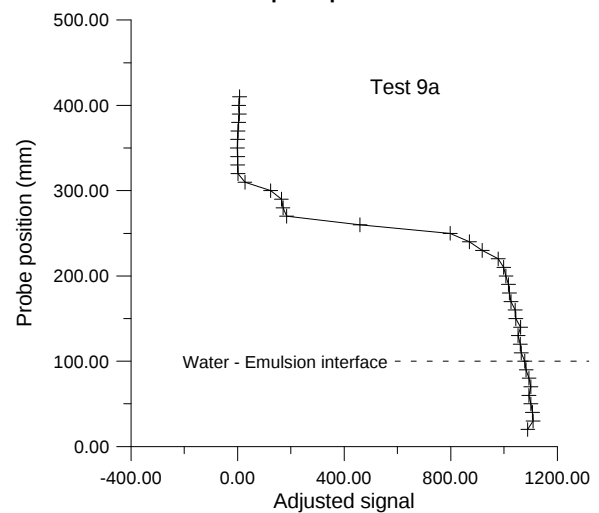


Figure 9: Adjusted signal where there is a signal gradient across the water/emulsion interface.

It is clear that three distinct signal levels are present. A signal value close to zero that coincide with air, a signal value somewhat less than 200 that coincide with the condensate and a signal value of approximately 1100 that coincides with the water zone. In data from test 6d the probe signal changes from one zone to the other over just a few electrodes as shown in Figure 8, thus exhibiting a large gradient in signal versus probe position.

In another test, 9a, the signals are not this easy to understand as shown in Figure 9. The gas/condensate and condensate/emulsion interfaces are readily seen, but there is no sudden change in signal value where the transition from water phase to emulsion phase occurs.

The signal gradient is the same on each side of the water/emulsion interface.

5.2 Understanding the signal.

The signal versus position plot normally exhibits relatively large gradients near interfaces in the system. However, in order to decide where

the position of an interface lies, a method of reading the plots must be defined.

In order to determine the positions of the interfaces some definition must be applied. In the analysis, the following criteria have been applied to determine the position of the interfaces:

- **Gas/Condensate Position:** First electrode to show change from air level moving down. ↓

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- **Condensate/Emulsion Position:** First electrode to show change from condensate level. Alternatively, first to show signal value above 200 moving down. ↓

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- **Water/Emulsion Position:** First electrode to show change from water level (sloping water level) moving up. ↑

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These definitions could have been different, and still the results would be good. It is, however, important to define how to analyse the results and be consistent to that definition.

5.3 Interface positions

The interface positions, predicted by the signal processing, can be compared with visually observed interface positions. This is shown in Figure 10.

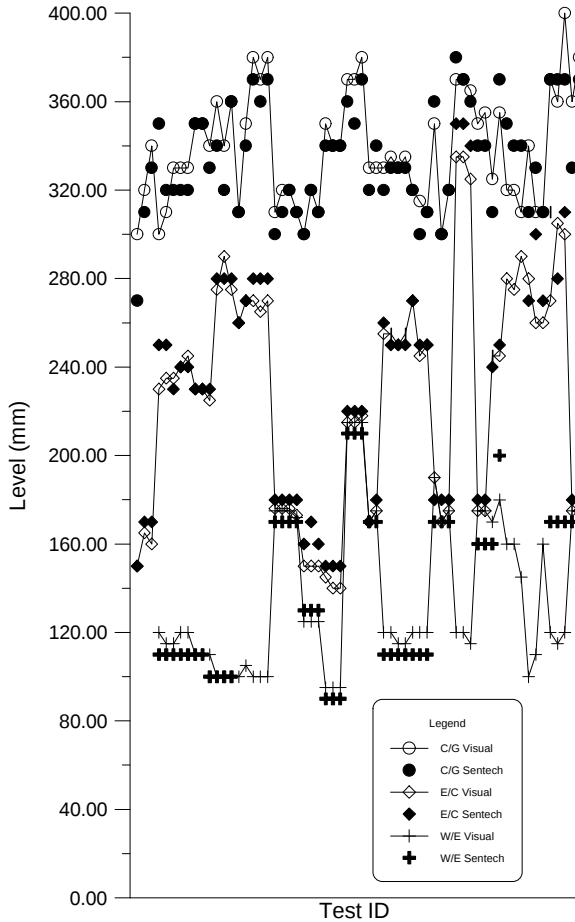


Figure 10: Measured and observed levels for all the tests.

Figure 10 shows how the interfaces changed during all the tests. Visual observations are points connected with solid lines. The results from the Sentech probe are shown as described in the legend.

The gas/condensate interface was sharp in all the tests. No foam was produced.

The condensate/emulsion interface was also easy to detect during the experiments. The water/emulsion interface, however, was often more blurred.

6. DISCUSSION

The signal from the sensor normally shows a change in slope at the position of interfaces. This gradient in the curve can then be used to determine the positions of interfaces in the system. However, in four of the tests it was not possible to see any change in

the signal versus position curve at the water/emulsion interface position, although it visually was observed. A plausible explanation for this is that there in fact was a concentration gradient in both the emulsion layer and in the water phase having the same slope. It is not clear, why the human eyes observe an interface in such a system.

The comparison between predicted and visually observed positions shows that the data are predicted within $\pm 20\text{mm}$ as shown in Figure 11. In terms of percentage error, the prediction is within $\pm 10\%$ as shown in Figure 12. The main reason for the rather high error is the size of each electrode, and that the electrodes are spaced at 10mm intervals. If the electrodes had been made smaller and fitted closer together, the resulting performance would improve.

In some of the tests, even the interface between air and condensate does not seem to be sharp on the signal versus position curve. This,

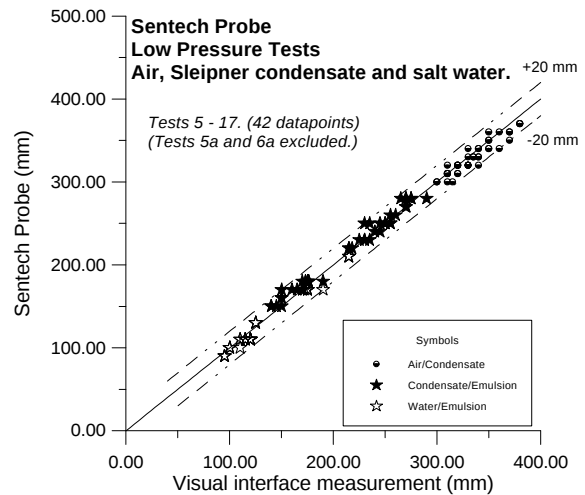


Figure 11: Predicted and observed interfaces (constant band error)

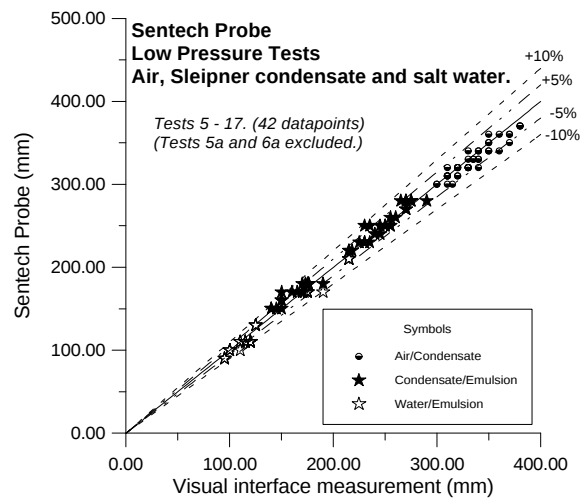


Figure 12: Predicted and observed interfaces (% band errors)

however, is often a direct result of one electrode being partly submerged in condensate. It is evident that the resulting signal value of the partially submerged electrode will show a signal somewhere between that of pure air and that of pure condensate. The result is that the change from one phase to the next takes place over a distance of three electrodes. However, if the size of the electrodes had been smaller, and the electrodes positioned closer, this kind of effect would not be as pronounced as it is in this set of results.

7. CONCLUSIONS

The capacitance sensor has shown that it reliably can detect the presence of gas, condensate and water near the sensor. If the fluid forms an emulsion, the probe gives a signal between that of water and condensate. The signal varies as a continuous function from the water phase to the condensate phase indicating varying water content in the emulsion layer.

The presentation of the raw data clearly shows the position of interfaces in the vessel. The signal versus time plot shows the location of the different layers in the vessel. This type of plot is of great value understanding the operating condition of separator vessels.

8. FUTURE WORK

The system has shown that it is able to operate at low pressures and give reliable signals that can be used to determine the positions of fluid interfaces in a separator. A high-pressure version of the probe will be installed in the Multi-Phase Flow Loop² of Norsk Hydro ASA, Porsgrunn, Norway. This system can operate at pressures and temperatures up to 120 bara and 140°C, respectively, with real hydrocarbon/water mixtures. The plan is that these tests will commence in January 1999.

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