A Portable Capacitance Probe for Detection of Interface Levels in Multi-Phase Flows – a Case Study

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Abstract *– This paper describes the design and construction of a portable probe for monitoring the dynamics of the multi-phase flows within horizontal oil-water separators and presents some preliminary results from the industrial tests of the prototype device. The detection of individual phases is based on the measurement of dielectric properties of the process media, by means of an array of capacitance sensors, which are distributed along the body of the probe. The measurements of electrical capacitance are performed using electronic circuitry, based on charge transfer principle, which was originally developed at UMIST for tomographic applications.*

Keywords: multiphase flow, interface detection, oil-water separators

1. INTRODUCTION

The progress in industrial tomographic techniques, over recent years, was driven by the investigations of very complex multiphase transport phenomena within pipelines or process vessels. In many practical applications, however, the geometry of phase distribution in the process equipment is already known. The problem of flow control can then be reduced, for example, to monitoring and maintaining the interface position between individual phases at a certain level. This is one of the most fundamental issues in process control; numerous examples can be given from as diverse areas as food processing, pharmaceutical and oil production industries.

The existing techniques for detection of individual phases utilise various principles of measurement. For example, mechanical arrangements such as floats or weights are sensitive to the specific density of phases. Pressure transducers can measure the changes in the pressure gradients across the heterogeneous layers (again due to varying specific density). Sonic or ultrasonic devices capture the differences in the propagation speed of a transmitted signal (time delay in receiving an “echo”). Capacitance and conductance sensors detect changes in the dielectric permittivity and conductivity of the media. A number of alternative methods such as microwave, nuclear magnetic resonance or gamma ray systems are widely described in the existing literature.

The choice of capacitance sensors, applied in the described probe, was dictated by their well-known reliability and robustness - they have no moving parts, can withstand high temperatures (several hundred degrees C) and pressures (well over 100 bars). Capacitance techniques work with a variety of media: liquids, powders, solid particles, slurries etc. The output signal from the sensors is practically instantaneous and, therefore, can be easily used as a feedback for control purposes.

The instrument presented here was designed and built bearing in mind the specific control needs of horizontal oil-water separators, widely used in both offshore and onshore petroleum installations. In this type of vessels, the oil and water mixtures are separated under the action of buoyancy forces, thanks to a sufficiently long “residence time”, and then divided into individual streams by means of a weir arrangement. However, both the composition and the stability of oil-water mixtures, entering a vessel, may vary widely over relatively short periods. Therefore, precise control over the levels of individual phases inside a vessel is required to prevent accidental cross entrainments of one phase into the production stream of another, as this can seriously affect the rig’s overall efficiency. It should be emphasised, however, that there are no fundamental difficulties in applying the technology and the design procedures described in this paper to many other industrial processes.

In the simplest case of a single phase detection the device for capacitance measurements may consist of a single electrode made in the form of a “dipstick”. Here the varying interface level is determined from the varying capacitance to earth. This type of probes is widely marketed by a number of manufacturers (*cf.*, for example, [1], [2] and [3]). Of course, the introduction of multiple phases (such as oil, water and their heterogeneous mixtures) into the vessel, equipped with these devices, leads to ambiguous readings.

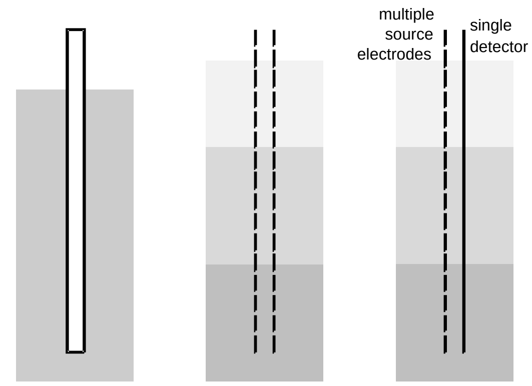
Several possible solutions to this problem have been suggested. References [4] and [5] describe two designs of multiple capacitance sensors forming vertical sets of identical ‘cells’. In this approach, the detection of individual phases is quite straightforward. The individual sensors (or “cells”) are evenly distributed across all phases and the resulting set of output signals allows “capacitance profiles” to be obtained. These are directly related to the configuration of layers inside a vessel.

Yang *et al.* [6] developed a slightly different design, which utilises an array of excitation (or source) electrodes facing a common detection electrode. Schüller *et al.* [7] proposed a probe in a form of a cylinder, with a number of ring-like segmented electrodes along the length, which gives a profile of capacitance between each electrode and infinity. The spatial resolution of the devices based on the concept of segmented electrodes is of the order of electrode spacing.

In general, the capacitance methods work very well for detection of multiphase flows of dielectric materials such as gas, foam and oil. The conducting fluids, however, such as produced water, “short” the sensors so that effectively the measured capacitance becomes 50% of the value for the electrode insulation. From the practical point of view, this limits the capacitance methods to detecting water in oil but not vice versa. Hammer *et al.* [8] claim that this difficulty may be overcome by using uninsulated electrodes, however it is not clear how this could be achieved in practical situations, where, the electrodes can be coated with oily deposits.

In the presented design of the capacitance probe, the authors explored the idea of segmented capacitance electrodes. In contrast to earlier work [4-6], the following modifications have been made:

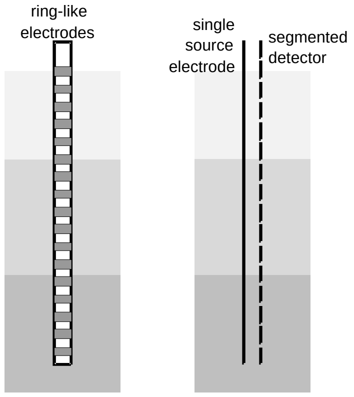
- The concept of addressing individual sensors has been re-examined. Unlike the probe described by Yang *et al*. [6], the current device utilises a common excitation electrode and a set of segmented detection electrodes, which are sequentially addressed by a multiplexer. This seemed to be a more logical solution from the viewpoint of obtaining a uniform electrical field scanning the space between electrodes.
- Guard electrodes, surrounding the detection electrodes were added to make the electrical field more uniform.
- Design of the probe was based on the numerical analysis of the electrical field. This indicated that the use of dielectric material for the sensors’ casing should be advantageous.
- Electronic circuitry, to measure the electrical capacitance, was based on the charge transfer principle [9,10] - similar to the original tomographic applications developed by UMIST.



single electrode in the form of rod [1,2,3]

vertically distributed cells [4,5]

arrangement developed by Yang *et al.* [6]



capacitance measured between each electrode and infinity [7]

current work

Figure 1. Various approaches to constructing capacitance level probes

Figure 1 shows schematically various approaches to constructing the capacitance interface level probes.

2. DESIGN PROCEDURES

The probe described in this paper was built to meet specific requirements imposed by industrial sponsors involved in this project, to allow further tests in a “medium-size” industrial vessel. It has been suggested that the probe should fit vessels between 1.0 and 2.0 m in diameter, working under “moderate” pressure and temperature conditions (up to 20 bar and 80^{O}C). In addition, the diameter of the probe should suit 2" nozzles, very common in the existing oil-water separators. From the interface detection viewpoint, the required spatial resolution was about 10 mm.

The initial design procedures concentrated on two major aspects: numerical simulations of the electrical field to maximise the performance of the instrument and selection of a reliable technology to manufacture the capacitance sensors.

2.1. Numerical simulations

Figure 2a shows the cross section of a probe, similar to that presented by Yang et al. [6], which served as a “starting point” for the numerical analysis. The probe consists of a stainless steel duct, which has two slots machined along its length, to allow process media to enter the sensing electrodes. The capacitance sensors are moulded inside two opposite halves of the probe by means of an epoxy resin potting compound. The stainless steel duct serves as both the mechanical protection and electrical shield (i.e. it is connected to zero potential).

Figures 2b and 2c show the results of the numerical simulations, performed using Ansoft EM Field Modeller. Figure 2b corresponds to the probe immersed in a medium of low relative dielectric permittivity (ε=1). Figure 2c corresponds to the probe immersed in a medium of high dielectric permittivity (ε=80). The graphs show the lines of equal potential. In the presented results the source electrode has been set at potential of 1V, the stainless steel body and detector were set at 0V. As one can see the change of medium leads to a dramatic change

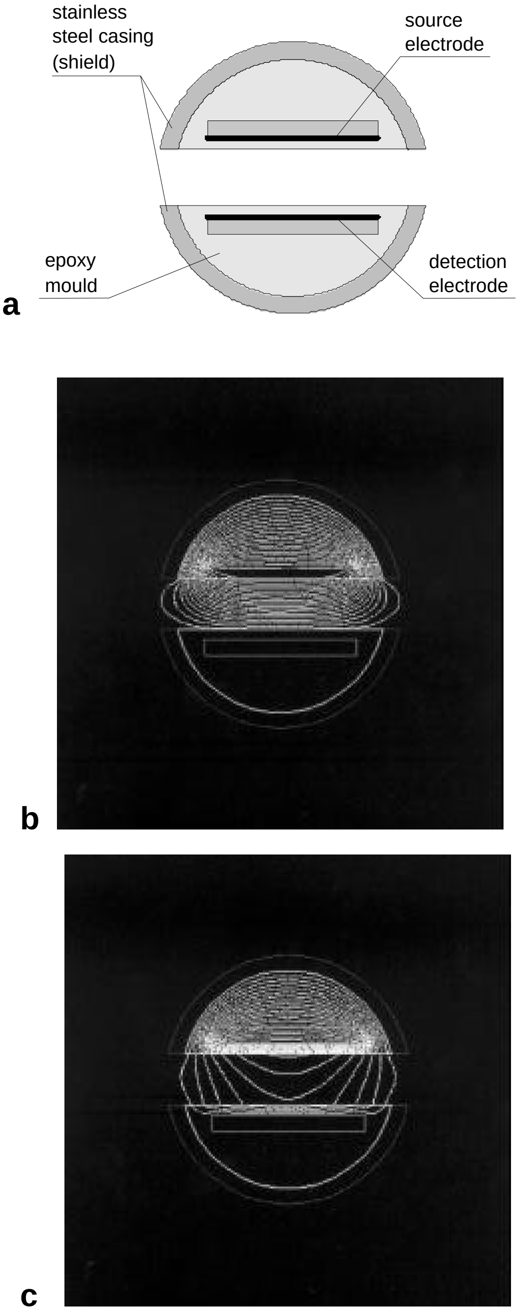


Figure 2. a) Cross-section of the probe, used as a starting point for numerical simulations; b) equi-potential lines for the probe immersed in the medium of ε=1; c) equi-potential lines for the probe immersed in the medium of ε=80

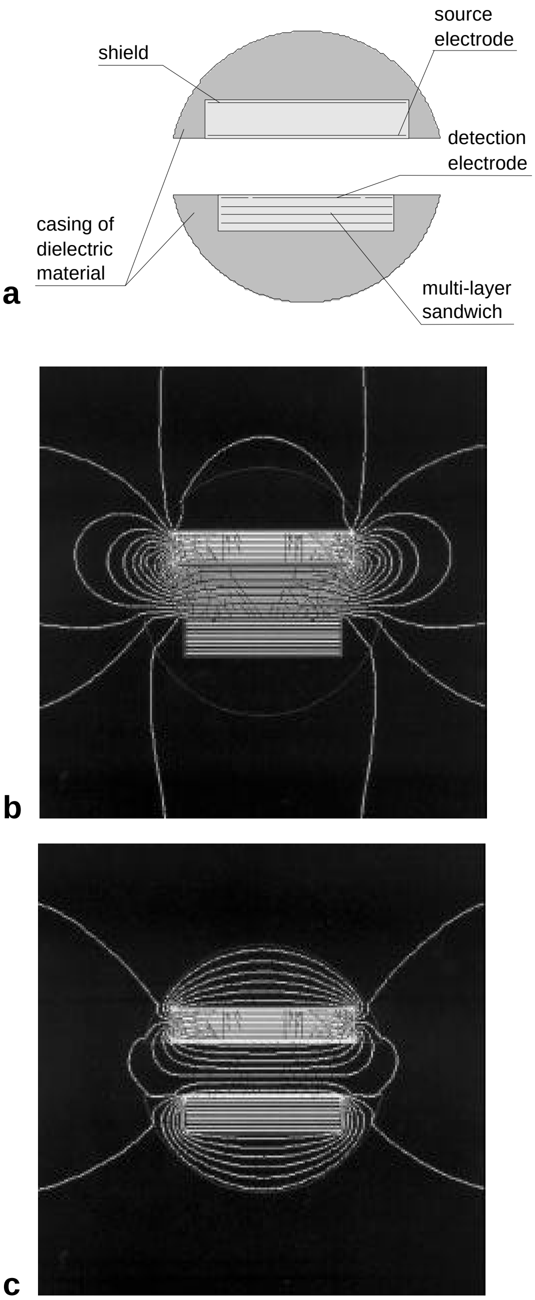


Figure 3. a) Cross-section of the current probe; b) equi-potential lines for the probe immersed in the medium of ε=1; c) equi-potential lines for the probe immersed in the medium of ε=80

from almost uniform electrical field, for low permittivity medium, to highly distorted field for high permittivity medium. A number of simulations have been performed to identify causes of this behaviour and to develop a better design for the probe, free from defects in the shape of electrical field.

The following conclusions were drawn. Firstly, the lines of electrical field, i.e. orthogonal to the equi-potential lines, tend to be pulled away from the detector towards the metal casing of the probe in the media of high permittivity (say higher then 15). This can be clearly seen in figure 2c. Secondly, the above effect is unavoidable, but can be reduced by covering the shield with a layer of dielectric material, and placing it behind the source electrodes [11]. Thirdly, the depth to which both the source and detection electrodes are embedded is critical - the thinner the electrode coating the less curvature of electric field is observed. In addition, it was found useful to increase the width of the source electrode in relation to the detector - this allows the shifting of the "curling" of the electrical field away from the centre of the detector.

Figure 3a shows the design of the probe based on the conclusions presented. The body of the probe is made of a dielectric material. The PCB inserts (*cf.* section 2.2) are glued into the prepared grooves. The source electrode is shielded from behind by an electrode placed on the back of the same PCB. The electrodes are embedded 0.5 mm below the surface of inserts. Figures 3b and 3c show the results of numerical simulations for the corrected probe design. Clearly, the change of the process media no longer leads to distortions of the electrical field.

It is worth mentioning that because, in the current design, there is a common source electrode and segmented detectors, the electrical field can be considered 2-dimensional. This is not the case for an arrangement with segmented source and common detector, where the electrical field has to be highly 3-dimensional.

Of course, the validity of such simulations is limited in the presence of conductive media as explained in the introduction. However, in the authors' opinion, performing such simulations should become an engineering practice during the design of any type of capacitance sensors.

2.2. Sensors fabrication

The design of capacitance sensors for the portable probe was based on application of the multi-layer Printed Circuit Boards (PCB). These were thought to be particularly useful for the following reasons:

- a compact and "elegant" way of providing electrical connections to the low-pressure "side" of the probe,
- a relatively easy design of the seal between high and low pressure areas – no need to accommodate numerous cables,
- high pressure and temperature specifications – the PCBs are typically manufactured at pressures of several tonnes per square inch and cured at 180^{O}C).

The layout of electrodes on the PCB inserts incorporated in the probe is given in figure 3. Here, the detection PCB consists of 24 electrodes (14x17 mm) surrounded by a guard electrode to protect the uniform electrical field between source and detection sides. Tracks leading to individual electrodes are sandwiched behind them and terminated at the end of the insert, providing solder points to connect signal wires. The insert containing the source electrode is slightly wider than the detection PCB and consists of 2 layers of a plain copper conductor: actual excitation and external shield.

During the last stage of PCB manufacture, the inserts were coated with a thin layer of epoxy laminate, to insulate the electrodes from the process media.

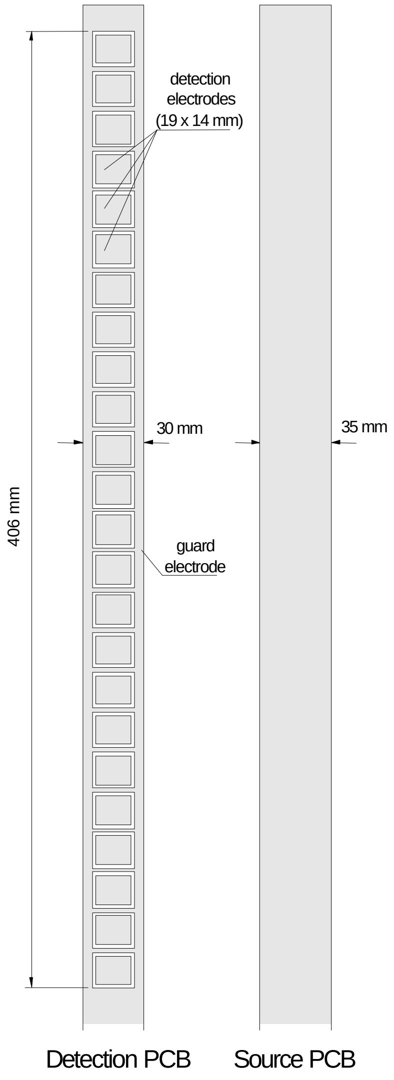


Figure 3. Layout of sensors on PCB boards.

3. CONSTRUCTION OF THE PROBE

Figure 5 shows the general view of the prototype capacitance probe (called later also UMIST probe for brevity). The diameter of the probe is 48 mm to fit 2" nozzles in the existing separators. The sensing part is built of dielectric material (Tufnol) with encapsulated capacitance sensors, as described in the previous section. The "active" length of the probe is 406 mm. A number of spacers (which can be seen in figure 5) keep the dielectric casings at a constant distance of 10 mm. The bottom end of the sensing part is terminated with a metal end-cap. The bond between these two is made permanent by an epoxy resin adhesive. The signal wires are soldered to the PCBs on the low-pressure side of the probe. The metal end-cap screws into a stainless steel tubing (extension), which in turn is fixed to a flange.

Figure 5. General view of the UMIST capacitance probe.

The signal wires are made of miniature coaxial cables, 1.2 m long, terminated with SMB coaxial connectors. During the probe operation, these are connected to the local box containing the driving electronics.

It is thought that in the final version of the probe, the enclosure containing the electronic circuitry can be mounted directly on the outside of the flange. The signal wires could then be even shorter thus reducing the stray capacitance.

The construction of the probe allows the exchange of "extensions" and flanges and, therefore, the immersion of the probe to various depths and its installation in various types of nozzles. This provides a certain degree of portability, very useful for "troubleshooting" tasks in existing plants.

4. EXPERIMENTAL SETUP

The experimental evaluation of the capacitance probe took place at the British Petroleum production facility, Wytch Farm, in Dorset, UK. The probe was inserted into the *Bridport Test Separator V1104*, through a 3" nozzle (6C) located at the bottom of the vessel, 300mm upstream from the water outlet. The typical throughput of the separator was between 700 and 800 barrels per day of oil-water mixture (usually about 80% of oil). The temperature of the vessel was kept at 42^{O}C and the working pressure was 5.9 barg.

Figure 6 shows a general view of the vessel and gives some idea about its size. Figure 7a shows the nozzle 6C with the probe already inserted into the vessel. The signal wires from the probe were connected to the local box of electronics. For safety reasons, the box was made of metal and had a sealed lid. The capacitance meter inside the box was powered by a local 24V DC source. The measurements were controlled by a remote PC (figure 7b) located in the "Equipment Room", about 80 metres, in straight line, from the separator. The length of the cables between the PC and the capacitance meter was about 200 metres. The communication between the devices was realised by means of two separate lines: one controlled the switching of the multiplexer between individual electrodes; the other carried the analogue signal (measured value of capacitance) back to the PC.

Figure 6. General view of the separator

The measurements obtained from the probe were compared with the existing, displacer type, device LIC 1101. The device works on the buoyancy principle, and is located outside the main body of the vessel, within a closed U-tube arrangement. The nominal range of the interface detection for LIC1101 is 355 mm and extends between 372 and 727 mm from the bottom of the

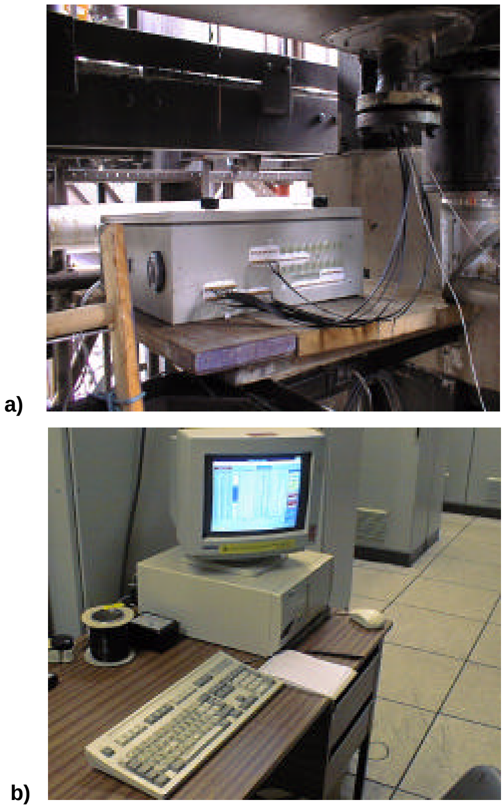


Figure 7. a) View from beneath the separator - the probe inserted into nozzle 6C and connected to the box with electronics; b) Control PC in the safe area.

vessel. The displacer is thought to indicate the oil-water interface position for specific gravity of oil 0.83 and process water 1.111 G/cm^3.

The length of the stainless steel extension, which supports the sensing part of the capacitance probe, was selected so that the range midpoints of both devices were on the same level. The range of the capacitance probe was slightly wider (406 mm) and extended from 347 to 753 mm above the vessel bottom. Figure 8 shows the measurement ranges for both devices.

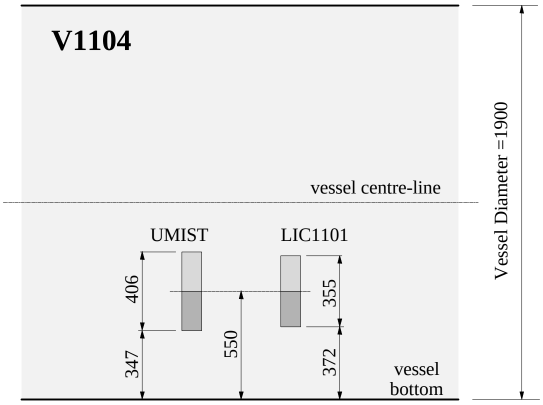


Figure 8. Measurement range for the UMIST capacitance probe and displacer LIC1101

5. RESULTS AND DISCUSSION

The experimental data described here were obtained during the tests conducted in July 1998. These were mainly focused on the overall performance of the probe and consisted of the oil-water interface measurements and comparisons with the readings from the displacer LIC1101.

The measurements of capacitance obtained from the UMIST probe were displayed in a graphical form on the screen of the control PC and then saved on the hard drive. Six examples of computer display, obtained during one day of the trials are shown in figure 9.

Each graph contains a table showing the electrode number and its reading in pF. The vertical “spectrum bar” next to the table serves as a visual help to interpret the readings. Two “profiles” next to the spectrum bar show the measured capacitance vs. electrode number (lower horizontal scale 0 to 10 pF) and the difference between each pair of neighbouring electrodes (upper horizontal scale –5 to +5 pF). The time of the measurement is displayed in the control panel on the right. The scanning frequency is software controllable but, in the experiments presented, the whole set of 24 electrodes was scanned approximately every 30 seconds.

The position of the interface was established by looking for the sharpest increase in the capacitance profile. This is made with the accuracy corresponding to the half of the electrode spacing (i.e. 8.5 mm), which was thought more than adequate for the application discussed. The objective of experiments such as depicted in figure 9 was to check the response from the probe while the oil-water interface was traversed along the full length of the device.

The data obtained from the displacer LIC 1101 are customarily saved in a designated file within the Wytch Farm monitoring system. These were retrieved after the tests to compare with UMIST probe.

Figure 10 shows the oil-water interface position (in mm above the vessel bottom), according to both devices, as a function of time, obtained during one of the tests. The black line corresponds to the capacitance probe, whereas the grey line corresponds to the float device. It can be clearly seen that the responses from both probes are in agreement with each other, as far as the general trend is concerned, however, there is also an offset present between the two. The flat parts on both curves (approximately between 14:00 and 16:00 hours) correspond to the interface position below the sensing range of the devices.

Figure 11 shows the data from two days of experiments presented as interface position obtained from UMIST probe vs. interface position from LIC 1101. Ideally, all data points in such a graph should lie on a straight line, y=x. In the actual situation the data points are clustered much above this line. Moreover, there can be three types of data points distinguished. Most of the points lie close to the regression line (marked as a grey line in figure 11) of the following equation:

$$U = 0.981 \times L + 115.3 \qquad (1)$$

where U is the position of interface according to UMIST probe (in mm), L is the position of interface according to LIC1101 (in mm) and the number 115.3 corresponds to the offset between both probes (also in mm).

The two sets of points: one along a vertical and another along a horizontal line (LIC1101 = 372mm and UMIST Probe = 753 mm, respectively) correspond to the oil water interface reaching the end of measuring range for a given device.

The data points, located below the regression line can also be accounted for. One has to remember that the UMIST probe was located only 300 mm from the water outlet from the vessel. The data points described were obtained during draining of the separator. Therefore, it is plausible to suggest that a strong vortex, present in the vicinity of the probe, is responsible for a slight displacement of the interface. Of course, such a displacement would not affect the displacer located externally to the vessel.

The existence of 115 mm offset between the devices suggests that the actual calibration of the displacer LIC1101 was not correct. Its performance depends on the density difference between oil and water and an unobstructed movement of the float in the float chamber. The measurements from the UMIST probe, on the other hand, rely on the physical contact of the media with the individual electrodes and therefore are more reliable in terms of interface measurements.

6. CONCLUDING REMARKS

In this paper the authors presented the design of an interface level gauge based on detailed analysis of the electrical field. It was shown that introduction of a dielectric material into its construction and tailoring the shape and size of electrodes leads to an enhanced performance.

The probe was evaluated in an industrial environment and the tests indicated that the principle of interface level monitoring using a device with segmented detection electrodes is correct. The results obtained from the UMIST probe and the displacer agreed very well – the directional coefficient obtained from regression was close to unity. However, there was an offset present due to inaccurate calibration of the float device.

The results described are of a preliminary nature and further tests are required to evaluate the probe's ability to detect the emulsion phase. This type of test was successfully made in a laboratory environment, using electrodes of a similar arrangement [12]. The operating conditions of the separator in Wytch Farm, however, were unsuitable for creating emulsions. Similarly, the long term performance of the probe, and the degradation of its characteristics in time have to be investigated.

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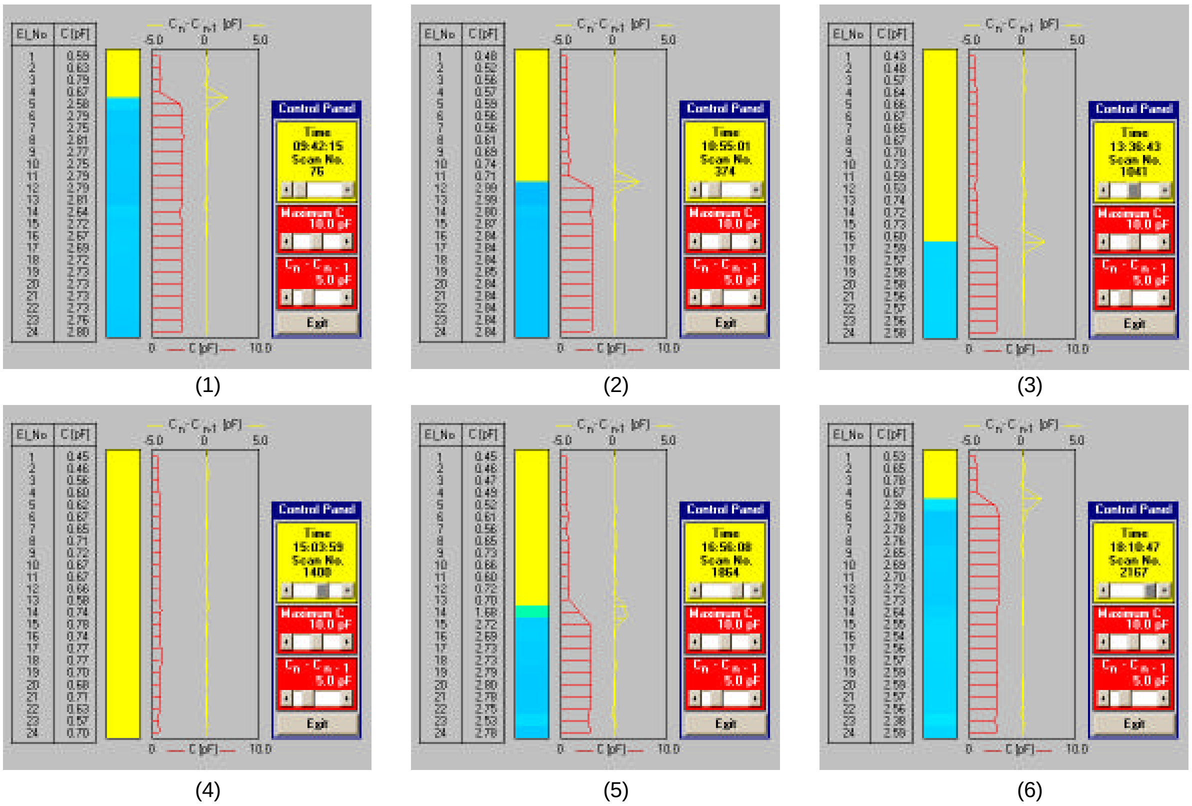
ACKNOWLEDGMENTS *– The authors would like to thank the EPSRC and the industrial sponsors grouped within the Advanced Research Partnership for supporting this work, in particular BP Exploration for hosting the field trials.*



(1)

El_No	C [pF]
1	0.59
2	0.63
3	0.79
4	0.67
5	2.58
6	2.79
7	2.75
8	2.81
9	2.77
10	2.75
11	2.79
12	2.79
13	2.81
14	2.64
15	2.72
16	2.67
17	2.69
18	2.72
19	2.73
20	2.73
21	2.73
22	2.73
23	2.76
24	2.80

Time 09:42:15
Scan No. 76
Maximum C 10.0 pF
$C_n - C_{n-1}$ 5.0 pF

(2)

El_No	C [pF]
1	0.48
2	0.52
3	0.56
4	0.57
5	0.59
6	0.56
7	0.56
8	0.61
9	0.69
10	0.74
11	0.71
12	2.99
13	2.99
14	2.80
15	2.87
16	2.84
17	2.84
18	2.84
19	2.85
20	2.84
21	2.84
22	2.84
23	2.84
24	2.84

Time 10:55:01
Scan No. 374
Maximum C 10.0 pF
$C_n - C_{n-1}$ 5.0 pF

(3)

El_No	C [pF]
1	0.43
2	0.48
3	0.57
4	0.64
5	0.66
6	0.67
7	0.65
8	0.67
9	0.70
10	0.73
11	0.59
12	0.53
13	0.74
14	0.72
15	0.73
16	0.60
17	2.59
18	2.57
19	2.58
20	2.59
21	2.56
22	2.57
23	2.56
24	2.58

Time 13:36:43
Scan No. 1041
Maximum C 10.0 pF
$C_n - C_{n-1}$ 5.0 pF

(4)

El_No	C [pF]
1	0.45
2	0.46
3	0.56
4	0.60
5	0.62
6	0.67
7	0.65
8	0.71
9	0.72
10	0.67
11	0.67
12	0.66
13	0.58
14	0.74
15	0.78
16	0.74
17	0.77
18	0.77
19	0.70
20	0.68
21	0.71
22	0.63
23	0.57
24	0.70

Time 15:03:59
Scan No. 1400
Maximum C 10.0 pF
$C_n - C_{n-1}$ 5.0 pF

(5)

El_No	C [pF]
1	0.45
2	0.46
3	0.47
4	0.49
5	0.52
6	0.61
7	0.56
8	0.65
9	0.73
10	0.66
11	0.60
12	0.72
13	0.70
14	1.68
15	2.72
16	2.69
17	2.73
18	2.73
19	2.79
20	2.80
21	2.78
22	2.75
23	2.53
24	2.78

Time 16:56:08
Scan No. 1864
Maximum C 10.0 pF
$C_n - C_{n-1}$ 5.0 pF

(6)

El_No	C [pF]
1	0.53
2	0.65
3	0.78
4	0.67
5	2.39
6	2.78
7	2.78
8	2.76
9	2.65
10	2.69
11	2.70
12	2.72
13	2.73
14	2.64
15	2.55
16	2.54
17	2.56
18	2.57
19	2.59
20	2.58
21	2.57
22	2.56
23	2.38
24	2.59

Time 18:10:47
Scan No. 2167
Maximum C 10.0 pF
$C_n - C_{n-1}$ 5.0 pF

Figure 9. A sequence of probe readings for varying oil-water interface levels.

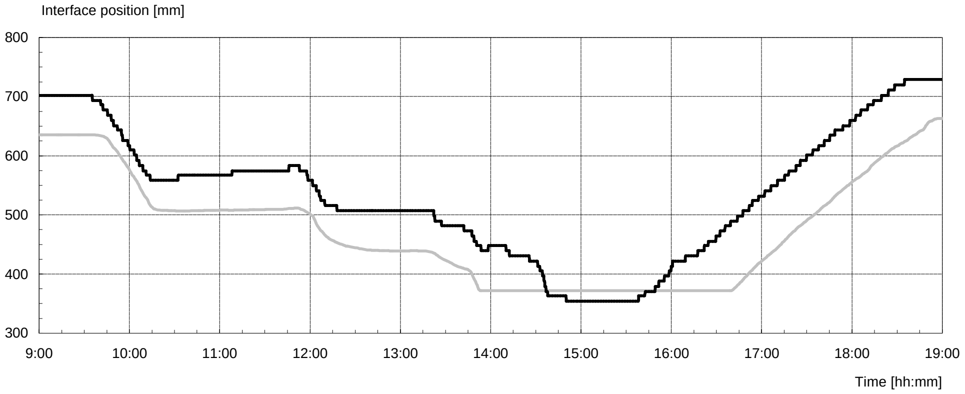


Figure 10. Interface positions vs. time obtained from UMIST probe (black line) and LIC1101 (grey line).

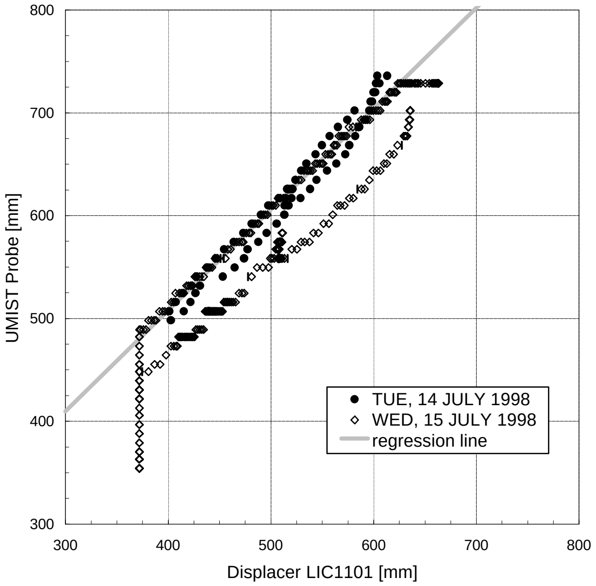


Figure 11. Comparison between readings from the UMIST probe and displacer LIC1101.