Multi-modality multi-interface level measurement

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Abstract. Crude oil separation is an important process in the oil industry. To make use of the separators efficiently, it is important to know their internal behaviour, and to measure the levels of multi-interfaces between different materials, such as gas-foam, foam-oil, oil-emulsion, emulsion-water and water-solids. A multi-modality multi-interface level instrument is presented, which is based on capacitance and electromagnetic measurements. Some key issues have been addressed, including the effect of salt content on measurement.

1. Introduction
Usually, crude oil from oil wells is sent to large separators (typically 1.5 - 3 meters in diameter and 3 - 10 meters in length) to separate gas, oil, water and other material, such as sand, aiming to extract oil. Most crude oil separators rely on gravity separation and the separation process takes a long time, say 3 hours or more, depending on the size of the vessel and quantity of the oil. To make use of the separators efficiently, it is important to know what is going on inside of the separators, i.e. it is important to measure the levels of multi-interfaces between different materials, such gas-foam, foam–oil, oil–emulsion, emulsion–water and water–sand.

This is particularly important for an offshore oil company. Crude oil from undersea contains significant amount of water, which is ideally separated on the platform rather than transported to the seashore, because the transportation process is very expensive and eventually water has to be separated from the oil. Because the space on offshore oil platforms is limited and expensive, effective monitoring and control of the crude oil separation process on offshore oil platforms will result in huge saving to the oil companies. Therefore, it is necessary to have a reliable instrument to measure multi-interfaces for the benefit of oil companies. Accurate measurement of levels and fluid components will also benefit the environment by reducing pollution.

2. Multi-modality sensor
The new sensor has two modalities: capacitance and electromagnetic. It consists of two identical rods, separated by 30 mm as shown in Fig.1 (a). The rods are selected to reduce the abstraction resistance to the liquid flow and to avoid the fouling problem. As a prototype, the length of the rods is 1 m long. Each rod comprises the following items: a Perspex tube, 20 coils, 20 capacitance electrodes with electric shields, and a supporting plastic tube, as shown in Fig.1 (b). Fig.1 (c) shows two arrays of capacitance electrodes and coils in the sensor. The main function of this system is to measure the level interfaces and the salinity of liquids.
2.1 Design of capacitance sensing elements

The designed capacitance electrodes have been verified by simulation using COMSOL. Fig. 2 (a) shows the simulation results when the electrodes occupy half of the internal circumference of the tube (50.3 mm wide). Simulation was also carried out for the electrode size of 27.15 mm and 12.6 mm. The results are shown in Fig. 2 (b) and 2 (c).

Based on the simulation results the dimensions of the capacitance electrode are chosen to be 27.15 mm \( \times \) 40 mm, giving an accuracy of \( \pm 4\% \) or better for a one meter long sensor. To reduce the number of connection wires of the capacitance electrodes, a design as shown in Fig. 3 is applied. Table 1 show the combination of the electrodes, which will be controlled by a microcontroller (PIC18F452).

![Figure 1: Multi-modality sensor](image)

The charge-discharge capacitance measuring circuit shown in Fig. 4 is used to measure the unknown capacitance \( C_x \). The unknown capacitance \( C_x \) is calculated from the potential difference between \( V_{\text{ch}} \) and \( V_{\text{disch}} \):

\[
C_x = \frac{(V_{\text{disch}} + e_1) - (V_{\text{ch}} + e_2)}{2fV_{\text{sup}}R_f}
\]  

(1)

where \( f \) is the switching frequency, \( V_{\text{sup}} \) is the maximum charging voltage, \( R_f \) is the feedback resistor and \( e_1 \) is the offset voltage associated with the CMOS switches.
3.2 Design of electromagnetic sensing elements

The distance between the excitation and detection coils is fixed by the selection of the distance between the capacitance electrodes, as shown in Fig. 1 (b). The sensing coil design parameters include the geometry of coil, operating frequency, applied current, material of the coil core and the number of coil turns. Fig. 5 shows the effect of the coil geometry on the magnetic flux and skin depth.

Table 1 Capacitance electrode combinations

| Excitation | Detection |
|------------|-----------|
| A          | 1 2 3 4 5 |
| B          | 6 7 8 9 10|
| C          | 11 12 13 14 15 |
| D          | 16 17 18 19 20 |

Figure 2: Simulation results, 30 mm between the rods with different electrode size

Figure 3: Capacitance electrode combinations

Figure 4: Charge-discharge measuring circuit

Figure 5: Effect of coil geometry on magnetic flux and skin depth
Fig. 6 shows the effect of the coil core material on the magnetic flux. The magnetic flux is significantly affected by the core material. By simulation, the inductance with ferrite coil core is 3.4 $mT$ and the inductance with air gap coil core is 38.8 $\mu T$. A total of 40 sensing coils are fabricated, 20 coils in each rod. The distance between the coils is 40 mm, giving a worst accuracy of $\pm 4\%$ for a one meter long sensor. The microcontroller is used to control the operation of the coils, allowing only one set of excitation - detection coils to work at a time and all other coils are grounded as shown in Fig. 7.

**Figure 6.** Effect of core material on magnetic potential lines

**Figure 7.** Coils circuit

3. **Experiment**

3.1 **Experimental set-up**

The preliminary experiment to test the performance of the sensor is conducted using an impedance analyser and a PC as shown in Fig. 8. For the experiment the conductivity of the salted water is 40 mS. The sensor was tested when it was (i) empty, (ii) full of water and (iii) full of oil in a frequency range from 1 kHz to 2 MHz. Fig. 9 (a) shows the measured capacitance at 900 kHz, when electrodes 1-7 are soaked in water, 8-12 in oil and 13-20 in air. There was no foam or emulsion layer. Fig. 9 (b) shows the impedance measurement at 900 kHz, when coils 1-7 are soaked in water, 8-12 in oil and 13-20 in air.

**Figure 8.** Sensor under test using PC and impedance analyser

3.2 **Salinity measurement**

Salinity is measured based on the effective conductivity of the liquid mixture using Maxwell’s model.

$$\sigma_{\text{eff}} = \sigma_{\text{oil}} \frac{2\sigma_{\text{oil}} + \sigma_{\text{oil}} - 2\nu_r(\sigma_{\text{oil}} - \sigma_{\text{oil}})}{2\sigma_{\text{oil}} + \sigma_{\text{oil}} + \nu_r(\sigma_{\text{oil}} - \sigma_{\text{oil}})}$$

(2)
where $\sigma_{\text{eff}}$ is the effective conductivity of the mixture, $\sigma_{\text{oil}}$ is the conductivity of the oil, $\sigma_{\text{w}}$ is the conductivity of the water and $v_f$ is the volume fraction of water in oil.

![Measured capacitance profile](image1)

(a) Measured capacitance profile

![Measured impedance profile](image2)

(b) Measured impedance profile

**Figure 9:** Measurement using impedance analyser

Simulation was conducted using COMSOL based on the electrical properties of heterogeneous mixtures (Jaworski 2005). The salinity of the mixture is calculated based on the effective conductivity (Perkin 1980).

\[
S = \sum_{j}^k a_j R_j^{1/2} + \frac{(T - 15)}{1 + k (T - 15)} \sum_{j}^k b_j R_j^{1/2}
\]

(3)

where $R_T$ is the conductivity ratio;

\[
R_T = \frac{\sigma(S, T, P)}{\sigma(35,15,0)}
\]

(4)

where $\sigma(S, T, P)$ is the conductivity of the mixture with practical salinity $S$ at temperature $T$ and pressure $P$ and $\sigma(35,15,0)$ is the conductivity of standard seawater with practical salinity 35 at 15°C and atmospheric pressure.

Fig.10 shows simulation results of the relationship between the percentage of salted water and the salinity. The solid line represents the salinity calculated by Matlab and the star line represents the salinity calculated by a salinity calculator (Tomczak 2000).

In the simulation, it is assumed that the temperature is 20°C and pressure is the atmospheric pressure.

**Figure 10:** Relationship between percentage of water and salinity
4. Conclusion
The existing systems for multi-interface level measurement have problems. The capacitance type has problems with high conductive water, temperature and fouling. The electromagnetic type has problems with measuring gas and oil and cannot detect the foam layer. This paper combines capacitance and electromagnetic sensors, to overcome the problems discussed above. The simulation and experimental results show that capacitance sensors can detect the interface between oil and gas, as well as between oil and low conductive water. Highly conductive water, electromagnetic sensors can detect the interface between oil and water but cannot detect the interface between oil and gas. It is very important to select the coils with same electrical specifications, so that they give the same results for one particular medium at a specified frequency. In conclusion, a multi-modality multi-level measurement sensor can be divided into sections, with capacitance modality at the top and electromagnetic modality at the bottom.

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