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Water Fraction Measurement Using a RF Resonant Cavity Sensor

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Abstract- We have tested the working principle of water fraction measurement using a Radio Frequency (RF) resonant cavity sensor. This technology allows us to determine the water fraction by the frequency shift of the first resonant peak in a non-intrusive way. The sensor operates with low power signals (1 mW) in the range of 100 through 400 MHz. Static measurements were done using a Scalar Network Analyzer (SNA) for water/oil and water/air static mixtures with fresh water and sea water. The measurement's uncertainty and the characteristic curves of the sensor's behavior were computed.

***Keywords*:** resonant sensor, resonant cavity, biphasic flow, radio frequency, water fraction meter.

I. Introduction

Conventional multiphase flow measurement systems operate after the separation of phases, measuring each flow using single-phase meters in petroleum production [1]. Such systems employ well established technology providing high accuracy measurements. On the other hand, multiphase flow metering can improve the petroleum production by continuously monitoring the wells, in addition to reducing the time and the space necessary to make the measurements [2], [3]. However multiphase measurement technologies are complex and limited because the measurement uncertainties rise mainly due to the complex flow pattern [4]. There are different technologies to estimate the percentage volumes of each phase of multiphase flow in the pipeline such as electric impedance and electromagnetic technology [4], [5]. Sensors based on the electromagnetic technology, like resonant sensors, are based on the dielectric properties of the multiphase flow in the RF and microwave range [6]. They are usually used in fluids containing water due to the large difference between permittivity of the water and those of other fluids, such as oil.

In this paper, we propose the use of a non-intrusive water fraction measurement method based on a resonant cavity sensor. The experimental results show that the RF resonant cavity sensor technology allows to determine the water fraction by monitoring the first resonance frequency. The uncertainty of individual measurements were computed and a polynomial identification was done in order to characterize the sensor's behavior.

II. Development

A. Working principle

Resonant cavities are closed metallic devices made in the rectangular or cylindrical shape, in which the energy is stored in the electromagnetic fields at high frequency. The resonance occurs at the frequency in which the excitation field will be in phase with the reflection components, resulting in a high standing wave pattern inside the cavity. This phenomenon occurs at distinct frequencies, corresponding to different propagation modes, denoted: Transversal Electric TE_{nml} and Transversal Magnetic TM_{nml} where n, m, and l, refer to a maximum electric field at a wave pattern in the cavity directions [6]. The resonance frequency of a cylindrical cavity can be determined by:

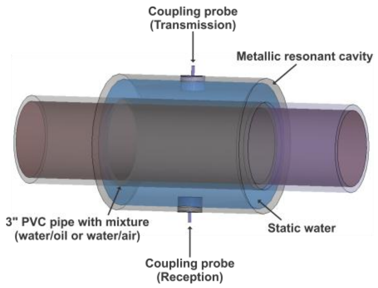
$$f_{r,nml} = \frac{1}{2\sqrt{\mu\varepsilon}}\left[\left(\frac{p_{nm}}{\pi a}\right)^2 + \left(\frac{l}{d}\right)^2\right]^{\frac{1}{2}} \quad (1)$$

where p_{nm} are mth-order Bessel functions of the first kind that vary according to the propagation mode, a is the cavity radius and d is the cavity length, both in meter, μ is the permeability of the medium defined as $\mu = \mu_o \mu_r$, where μ_o is the magnetic permeability of free space and μ_r is the relative permeability of the material, ε is the electric permittivity, being $\varepsilon = \varepsilon_o \varepsilon_r$, where ε_o is the permittivity of free space and ε_r is the relative permittivity of the material. The relative permittivity ε_r is a complex value, usually represented by $\varepsilon_r = \varepsilon_r' + j\varepsilon_r''$, where the imaginary part stands for the loss of the material.

In general, the RF resonant cavity sensor allows the determination of the water fraction by measuring the first resonant frequency associated to a given propagation mode. The variation of mixture permittivity is proportional to the quantity of water in the mixture. This is possible due to the larger difference between the relative permittivity of water ($\varepsilon_w \sim 81$) and that of other fluids, e. g. oil and air ($\varepsilon_{oil} = 2{,}2 - 2{,}5$, $\varepsilon_{air} = 1$, respectively) [2]. The relative permittivity of the mixture increases with the water content. It gets close to 81 when there is 100% of water. Conversely, the relative permittivity decreases getting close to the other fluid value.

The sensor was built as depicted in Figure 1(a), where we can see a 3" PVC cylinder inside a 5" metallic cylinder with 15 cm length and was designed to resonate around 300 MHz for the TE111 resonant mode. The photograph of implemented prototype is in Figure 1(b) as detailed in [7]. The resonant frequency in that case is given by (2), where c is the speed of light in vacuum and ε_m is the relative permittivity of the mixture inside the sensor.

$$f_{r,TE111} = \frac{11.3846c}{2\sqrt{\varepsilon_m}} \quad (2)$$



(a)


(b)

Figure 1. Sketch (a) and photograph (b) of the resonant cavity sensor.

B. Analysis methodology

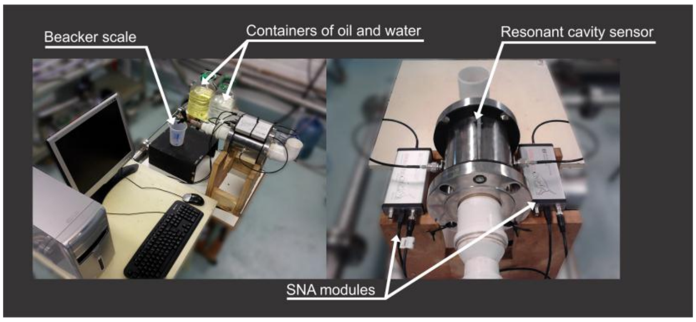
In order to validate the stand-alone operation of the sensor, we carried out several water/oil and water/air static measurements with fresh water and sea water using a transmitter (Signal Hound USB-TG44A) and a receiver (Signal Hound USB-SA44B) from Test Equipment Plus. The transmitter and receiver modules were configured to operate as a Scalar Network Analyzer (SNA), powered and controlled by a computer using a USB cable, and configured to perform a frequency sweep from 100 to 400 MHz with 500 kHz step size. The electromagnetic signal is injected to and received from the sensor through 50 ohm coaxial cables. A beacker scale was used to measure the amounts of oil and water. Details about the experimental measurement set-up as well as the block diagram of the set-up are shown in Figure 2(a) and (b) respectively. The Signal Hound modules measure the magnitude of the transmission coefficient (S_{21}) for the water concentration ranging from 0 to 100%, with steps of 10%. The experiment was repeated several times in different days.

C. Experimental results and characterization

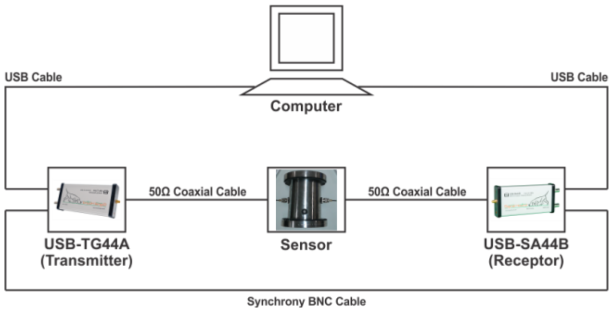
Thirty measurements were carried out for each mixture in different days. The standard deviation from the average values of the frequency of first resonant mode for each concentration of fresh water/oil, fresh water/air, sea water/oil and sea water/air mixtures are plotted in Figure 3(a), 3(b), 3(c), and 3(d) respectively. The percentage of standard uncertainty for the fresh water and sea water mixtures are shown in Figure 3(e) and (f) respectively. The resonant frequency corresponding to the first mode resonance is plotted against the water fraction in Figure 4(a) for all water/oil fraction scenarios, as well as the signal magnitude from each resonant frequency in Figure 4(b).

In order to characterize the sensor's behavior via experimental measurements, the measurements were fitted in a 5th order polynomial interpolation given by (3), whose coefficient values are showed in Table 1 for each mixture, where w_f is the water fraction and f_r is the resonant frequency.

$$w_f(f_r) = p_1 f_r^5 + p_2 f_r^4 + p_3 f_r^3 + p_4 f_r^2 + p_5 f_r + p_6 \quad (3)$$



(a)



(b)

Figure 2. Details of the experimental set-up (a) and a block diagram of the implemented set-up (b).

Table 1. Coefficients of the 5th order polynomial that fitted each mixture.

Coefficients	Fresh water / Oil	Fresh water / Air	Sea water / Oil	Sea water / Air
p_1	$-1.7984 * 10^{-5}$	$-1.4185 * 10^{-5}$	$-3.5568 * 10^{-6}$	$-5.6531 * 10^{6}$
p_2	$1.9273 * 10^{-2}$	$1.5347 * 10^{-2}$	$3.7039 * 10^{-3}$	$5.8659 * 10^{-3}$
p_3	-8.2630	-6.6402	-1.5421	-2.4328
p_4	$1.7715 * 10^{3}$	$1.4362 * 10^{3}$	320.8959	504.0977
p_5	$-1.8993 * 10^{5}$	$-1.5529 * 10^{5}$	$-3.3371 * 10^{4}$	$5.2185 * 10^{4}$
p_6	$8.1462 * 10^{6}$	$6.7157 * 10^{6}$	$1.3876 * 10^{6}$	$2.1594 * 10^{6}$

As seen in Figure 3(a) to 3(d), the standard deviation for the oil mixtures is larger than the air mixtures, especially at low water fractions using fresh water. In the last case the resonance below 50% of water almost disappears, so that the accuracy of the resonance peak identification becomes poor. In low water fractions the measurements of sea water mixtures is more accurate than fresh water mixtures because the first resonance from the sea water mixtures is more selective than the fresh water mixtures. In general, the main uncertainty source from the oil mixtures is due the contamination of water by the oil when the measurements were done.

The percentage of standard uncertainty from the fresh water and sea water mixtures illustrated in Figure 3 show that the uncertainties from the oil mixtures are higher than those of air mixtures in almost all range of water fraction except above 55% from the fresh water mixtures when the uncertainty for the oil mixtures become lower than air mixtures. Analyzing the graphic in Figure 4(a) we can observe that the dynamic interval of the frequency shift from the sea water mixtures is larger than fresh water mixtures and the first resonant frequency occurs approximately 15 MHz below. This behavior can be investigated taking into account equation (2) where the resonant frequency is inversely proportional to the square root of the relative permittivity of the mixture.

In that case, the imaginary part of the permittivity of the sea water in the frequency range from 100 to 400 MHz becomes higher than the imaginary part of the permittivity of the fresh water such that the resonant frequency becomes lower than the resonant frequency of the fresh water mixture.

Another characteristic of the sea water is the higher attenuation that occurs above 50% of water fraction due to the large signal absorption caused by the presence of large conductivity in the middle as we can see in Figure 4(b).

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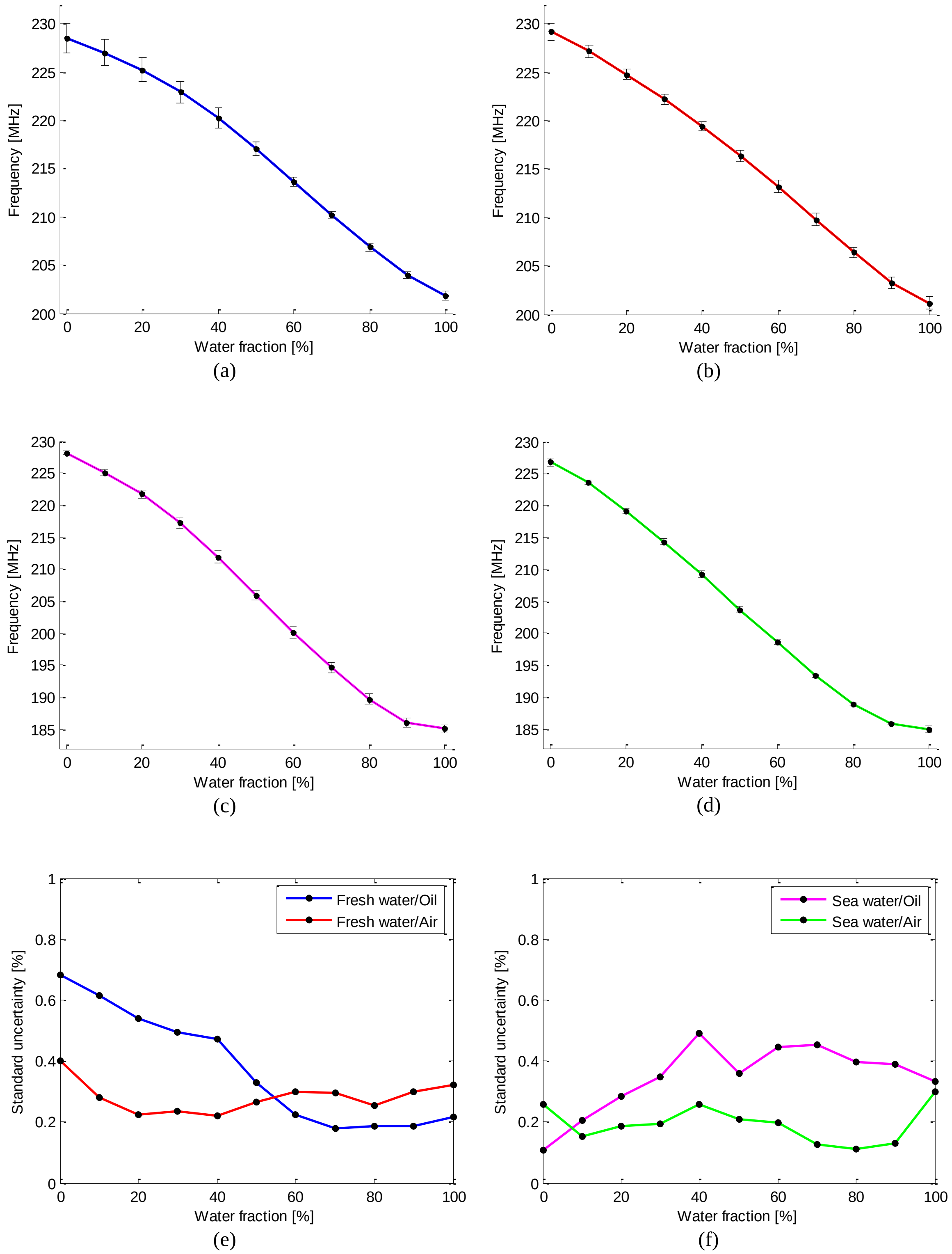
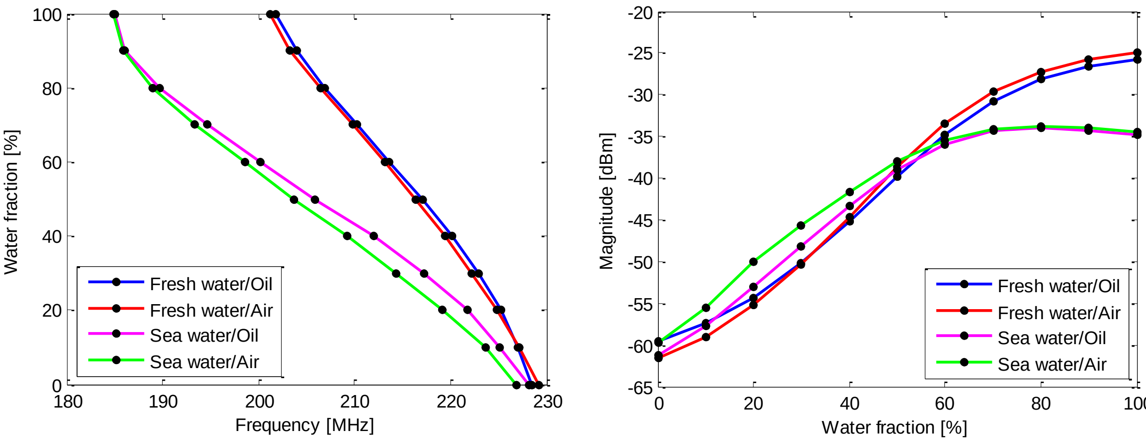


Figure 3. Standard deviation from the average values of the frequency of first resonant mode for fresh water/oil (a), fresh water/air (b), sea water/oil (c), and sea water/air (d) mixtures. Percentage of standard uncertainty for the fresh water (e) and sea water (f) mixtures.



(a) (b)

Figure 4. A comparison between all curves of the water fraction as function of resonant frequency (a) and signal magnitude as function of water fraction (b).

II. Conclusions

Several measurements were carried out to define the range and standard uncertainty of a RF resonant cavity sensor. The standard uncertainty average values were computed varying water fraction of the mixture. Some uncertainty sources such as variation of environment temperature, the scale of beacker used to remove the liquid from the sensor, the accuracy of SNA and the possible emulsion between the water and oil interface that could be considered a third phase, were neglected. It can be seen, for all experiments, that the total shift in resonance frequency for the water fraction varying from 0 to 100% is around 30 MHz for fresh water mixtures and about 45 MHz for sea water mixtures. These results show that the sensor has a good dynamic interval, especially in the presence of salt water. We can see that there is more accuracy from results with water/air mixtures for all measurements. A possible reason for this result is due to the contamination of water when the measurements with oil were done. We can also conclude that the accuracy in low water fraction is better in the presence of sea water because the resonance curves become more selective than with fresh water. All the standard uncertainty computed remained below 1%. One possible application of this sensor is to monitor the quantity of water into a producing oil well in order to determine when the injected water, necessary to maintain reservoir pressure in the producing well, appears at the output. This way, the proposed sensor works as a water-cut meter for the oil industry.

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