

Measurement of water volume fraction in oil-water upward flow by using microwave cylindrical resonant cavity

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Abstract

A microwave resonant cavity was used for the determination of water volume fraction in oil-water upward flow, the frequency shift and changes in the quality factor of the cavity resonator were the vital parameters. During the experiments, the flow rates of silicon oil were 75, 100 and 125 L/min and the water volume fraction ranged from 0 to 20.1%. The relative error between the predicted and measured water volume fraction of oil-water upward flow ranged from -3.9% to 4.32% and -2.58% to 4.44% for the TM₀₁₀ and TM₁₁₀ modes.

1. Introduction

It is a requirement in the oil and gas industry to minimize the water content in crude oil as it is associated with corrosion issues in downstream processing units as well as costs of transportation. It in fact is a part of the quality defining parameter of the crude. For this reason, a reasonably accurate measurement of water in crude oil is required. In addition, monitoring water cut at various points during the processing facility may optimize the separation efficiency in oil production operations [1]. Crude oil usually contains oil, gas and water components, and it is difficult to timely and accurately measure the fraction of each component in flow.

Microwaves are electromagnetic waves having a wavelength in the approximate range from 1mm to 1 m and occupy the region between infrared and radio frequency wavelengths [2]. Microwave sensors are used for a wide range of applications (1) measurement of distance, (2) movement, shape, and (3) particle size, but the largest group of applications are related to measurement of material properties [3]. The major advantage offered by microwave sensors is the capability to characterise materials non-destructively, in a contactless manner, without posing any health hazard to the personnel.

Microwave measurement techniques are low power applications of microwave energy. The complex effective permittivity of crude oil, which is closely related to the water volume fraction, can be measured using microwave techniques and relies in the great difference of dielectric properties between water and oil.

Therefore, the effect that water volume fraction has on the microwave characteristics of crude oil can be established through complex permittivity measurements [4]. Yang [5] described an oscillator load-pull to accurately determine the water-cut of an oil-water emulsion and discussed the necessary microwave oscillator source and control electronics. Avila [6] determined water fraction measurement by the frequency shift of the first resonant peak in a non-intrusive way based on a radio frequency resonant cavity sensor. Oon [7] utilised the resonant frequencies that occurred in a cylindrical cavity and monitored the changes in the permittivity of the measured phases to differentiate between the volume fractions of air, water and oil. Ashton [8] developed a prototype non-intrusive microwave multiphase flow meter for measurement of oil, water and gas flow rates on production pipelines. Hogan [9] developed a real-time, non-intrusive multiphase dielectric meter capable of measuring the dielectric properties of different mixtures of oil, gas and water in full well stream flow. Wylie [4] developed an electromagnetic cavity resonator-based sensor, which was non-intrusive and transmitted low power (10 mW) radio frequencies in the range of 100-350 MHz, to detect the pipeline contents using resonant peaks captured instantaneously. Although these studies, including static and dynamic experiments, have proved that water-cut measurements using microwave techniques are possible, they have not provided any quantitative correlation that could be actually used for the water-cut determination of upward oil-water flow. The present study focused on the upward oil-water flow and a cylindrical resonant cavity operating at frequencies between 100 MHz and 2 GHz

was proposed to measure the water volume fraction in upward oil-water flow and helped derive a semi-empirical correlation that could be utilised in the fast and accurate determination of water-cut in oil water mixtures.

2. Laboratory Setup

2.1 Resonant cavity and vector network analyzer

During a microwave resonance there is a balance between the energy stored and the energy dissipated in the resonator. Microwave resonators are used in a variety of applications, including filters, oscillators, frequency meters and tuned amplifiers [10]. The microwave resonator, which is used in the present study, is a common type of cylindrical cavity resonator. Various resonant modes like TM (transverse magnetic) and TE (transverse electronic) modes can exist simultaneously in the cavity resonator and each one with its own resonant frequency. The electromagnetic field pattern that correspond to each one of these resonant frequencies is termed mode:

$$\text{TE mode: } f_{mnl} = \frac{1}{2\pi\sqrt{\mu\epsilon}} \sqrt{\left(\frac{p'_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad (1)$$

$$\text{TM mode: } f_{mnl} = \frac{1}{2\pi\sqrt{\mu\epsilon}} \sqrt{\left(\frac{p_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad (2)$$

Where l , m and n are the number of variations in the standing wave pattern in the cavity directions, μ and ϵ are the permeability and permittivity of the material, a and d is the internal radius and height of cylindrical resonant cavity, p_{nm} is the m^{th} root of the Bessel function of n^{th} order, p'_{nm} is the m^{th} root of the derivative of Bessel function of n^{th} order.

The modes used in the present study are the TM_{010} and TM_{110} mode and the resonant frequencies of the unloaded TM_{010} and TM_{110} mode were 937MHz and 1.49 GHz respectively and correspond to the cavity dimensions.

In order to observe the relationship between insert loss and frequency, the scattering S_{21} parameters, which is the ratio of output and input power, were collected with the use of a Vector Network Analysers (VNA). S parameters are related to the reflected power and transmitted power in a microwave network as a function of frequency. The “Network” could be a coaxial cable, passive antenna, active amplifier, microwave filter, etc. The S parameters have magnitude and phase. Typically, magnitude is measured in dB and phase is measured in degrees.

The system was arranged by connecting network analyser and resonant cavity with two cables (Figure 1).



Figure 1: Measurement system

Figure 2 shows the resonant cavity, which is made of copper and has non-intrusive antennas. The energy of microwave was set to 20 dBm by the use of network analyser, the IF Bandwidth and averaging factor were adjusted to 100Hz and 4.



Figure 2: Resonant cavity

2.2 Liquid-liquid flow facility

Experiments were carried out on the liquid-liquid flow facility at the laboratory of the Faculty of Engineering in the University of Nottingham. Figure 3 displays the schematic diagram of this facility. It mainly consists of liquid supply systems, flowmeters, regulating valves, test sections and a separator. Silicon oil and water were supplied separately from two storage tanks, and the flow rates are then measured using electromagnetic flow meters immediately before the mixing unit. After the mixer where a fine dispersion is obtained, the oil-water mixture flows through a 2.8 m long vertical test section and a 4.5m long horizontal test section, and the inner diameter of these two test sections are 34 mm and 63 mm respectively. Resonant cavity with Plexiglas tube is placed at 1050 mm downstream of the bottom bend of the U-type tube (refer to Figure 3). A sampling valve is fitted at the lower end of the U section. Oil flow rates reported here were 75, 100 and 125 L/min, while varying the water fractions from 0% to 20.1% for each oil flow rate. After the test sections, oil-water mixture finally flowed into the separator and returned to the storage tanks for recycling use.

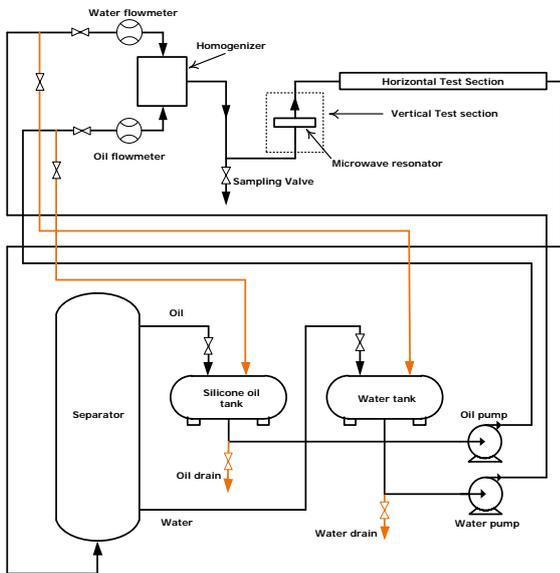
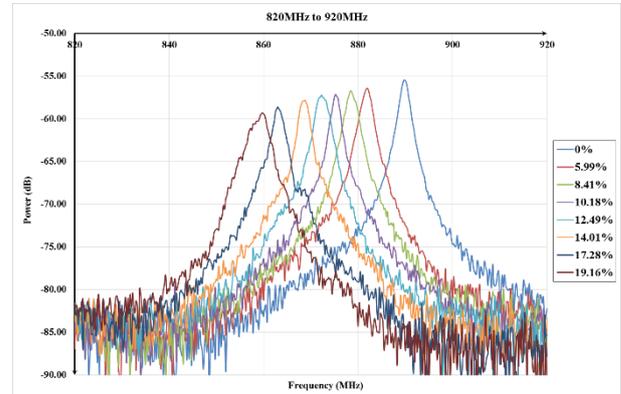


Figure 3: Schematic diagram of the liquid-liquid facility

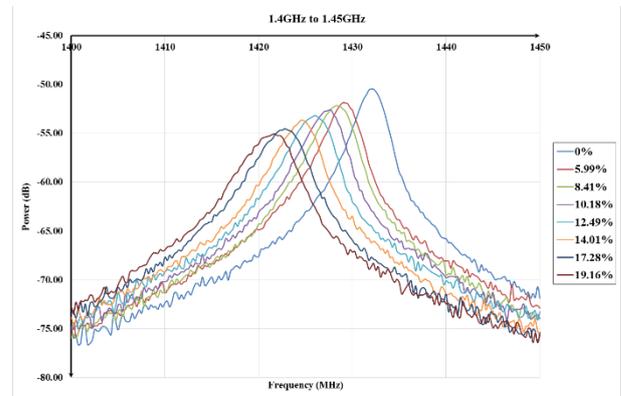
3. Results and discussion

In the experiments, flow rates of silicon oil and water were set at first, and then frequency and power of the peaks were collected three times after the oil and liquid flow rates stabilised. In order to acquire the actual water volume fraction of the flow in the pipe, taking a liquid sample was a necessary process when the collection of frequency and power was finished. After getting the sample, waiting for 30 minutes for the separation. And then the oil was on the top and the water was at the bottom, then majority of oil was poured into a beaker and the remaining oil-water mixture was poured into a measuring cylinder. Finally measuring the density of oil and weighing the beaker and cylinder, the volume of water and water-cut could be calculated.

Figure 4 display the resonant peaks of the cavity resonator for oil flow velocity which was 125L/min and the others flow rates showed the similar trend. According to the figures, as the increased of the water fraction, resonant frequencies continuous shift from approximately 890 MHz to 860 MHz and 1.433 GHz to 1.422 GHz. In addition, the amplitude of the resonant peaks also decreases by about 5dB with the increase of the water fraction. It means that the variation of water fraction in oil-water fraction could be described by the frequency shift and the amplitude decrease.



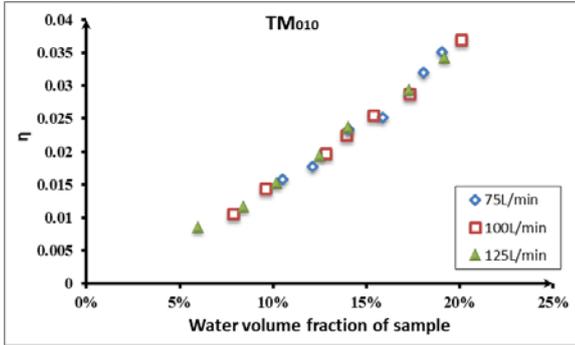
(a) TM_{010} mode, $u_{oil}=125L/min$



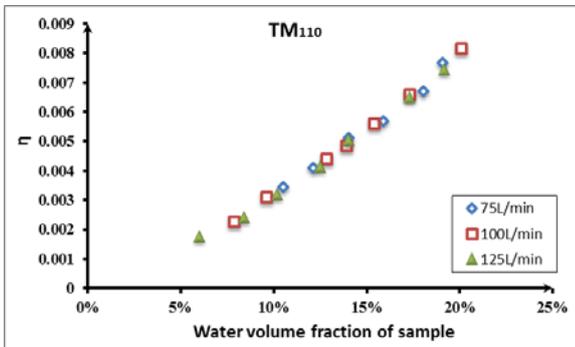
(b) TM_{110} mode, $u_{oil}=125L/min$

Figure 4. Resonant peaks of the cavity resonator

In order to describe the frequency shift due to the different water-cut, $(f-f_0)/f_0$, termed as η , was introduced here to give the approximate fractional change in resonant frequency, where f and f_0 were the resonant frequency of loaded and unloaded cavity respectively. η also was an important parameter in the simple perturbation theory of the resonant cavity to measure water cut due to the relationship between the resonant frequency and the dielectric property of the fluids. Although the system used in this study was not strictly complying with the simple perturbation theory criteria, any changes in the complex permittivity can be traced via the changes in frequency shift according to Figure 4. Figure 5 (a) and (b) show the η versus water volume fraction of the liquid sample and the deviations of each points. All the data points in these two figures were the average values of the three times measurement and the biggest standard deviation of each η was 0.0011.



(a) TM₀₁₀ mode



(b) TM₁₁₀ mode

Figure 5. Relationship between η and water volume fraction

Data points were overlapping in Figure 5, which indicates that although the oil and water flow rates were different, the performance of resonant cavity only depended on the water fraction of the mixture based on the former analysis. Therefore, water volume fraction, θ , could be calculated by using resonant frequencies of different peaks and two equations (Eq. (3) and (4)) were established based on half numbers of the data points which were selected random.

$$TM_{010} : \theta = -65.805\eta^2 + 7.8178\eta - 0.002 \quad (3)$$

$$TM_{110} : \theta = -1127.6\eta^2 + 32.702\eta + 0.008 \quad (4)$$

The performance of the above equations with the other data points were displayed in Figure 6. Results showed that the relative deviations between the predicted and actual water-cut ranged from -3.9% to 4.32% and -2.58% to 4.44% for TM₀₁₀ and TM₁₁₀ mode respectively, which indicated that the resonant cavity could be applied in the prediction of oil-water upward two phase flow and the accuracy was acceptable.

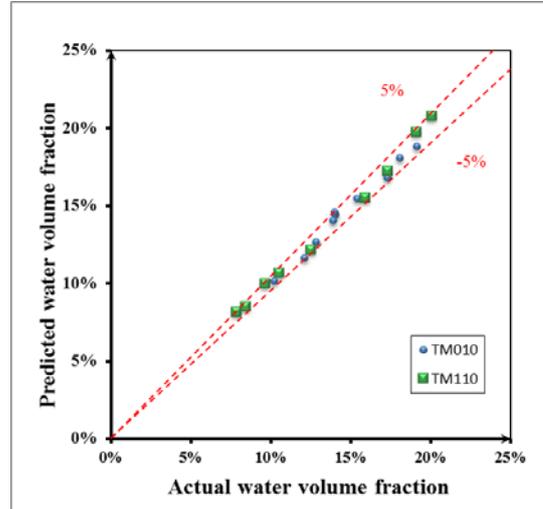


Figure 6. Performance of equation (3) and (4) in the measurement of water volume fraction

Due to the difference in the velocities of oil and water, slip may exist in the oil-water upward flow and water volume fraction measured using the microwave resonance cavity would be different from the values computed using the inlet flow rates or even from the sampling. In order to check whether the slip had affected the volume fraction measurement, water-cut from sampling and reference meters were compared as shown in Figure 7. From Figure 7 we can observe that the water-cut determined via sampling was very similar to the one determined by the reference meters which indicated that for the conditions of the experiments in the present case, there was almost no slip in the upward oil-water flow.

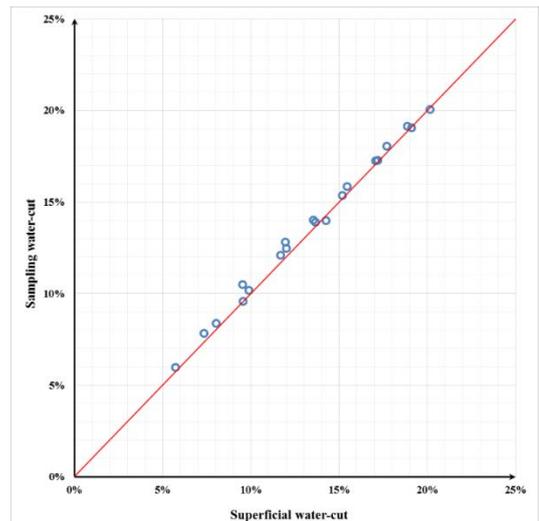


Figure 7. Sampling and superficial water cut

4. Conclusion

Water volume fraction of oil-water mixture was measured by using a cylindrical resonant cavity. The results showed that the resonant frequency was sensitive

to the variation of water cut with very good repeatability. The experiments of the oil-water flow indicated that the measurement of water content in the continuous flow it was feasible and robust and was not affected by the changing flow rates. Two semi-empirical equations were established for water-cut determination corresponding to the change of two resonant modes in the resonator. The relative error between the measured and the predicted water volume fraction in oil ranged from -3.9% to 4.32% and -2.58% to 4.44% for TM₀₁₀ and TM₁₁₀ mode respectively.

Acknowledgments

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