Experimental study on a feasibility of using electromagnetic wave cylindrical cavity sensor to monitor the percentage of water fraction in a two phase system

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Abstract

This study proposed a microwave sensor system to monitor single and two phase flow systems. The microwave sensing technology in this study utilises the resonant frequencies that occur in a cylindrical cavity and monitor the changes in the permittivity of the measured phases to differentiate between the volume fractions of air, water and oil. The sensor system used two port configuration S_{21} (acted as transmitter and receiver) to detect the fluids inside the pipe. In principle, the strong polarity of water molecules results in higher permittivity in comparison to other materials. A tiny change of water fraction will cause a significant frequency shift. Electromagnetic waves in the range of 5 GHz to 5.7 GHz have been used to analyse a two phase air-water and oil-water stratified flow in a pipeline. The results demonstrated the potential of a microwave sensing technique to be used for the two phase systems monitoring. A significant shift in the frequency and change in the amplitude clearly shows the percentage fraction change of water in the pipe. The temperature study of water also demonstrated the independence of microwave analysis technique to the temperature change. This is accounted to overlapping modes negating the affect. Statistical analysis of the amplitude data for two phase systems shows a linear relationship of the change in water percentage to the amplitude. The electromagnetic wave cavity sensor successfully detected the change in the water fraction inside the pipe between 0-100%. The results show that the technique can be developed further to reduce the anomalies in the existing microwave sensor.

Keywords: Multiphase flow meter; electromagnetic waves; resonant cavity sensor; microwave sensor; water fraction monitoring; non-invasive monitoring.

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1. Introduction

During the oil extraction, water and gas are produced as by-products. To maximise the production of oil from a reservoir, water and gas are often injected into the well. Water is used to maintain the pressure whereas the gas is used to reduce the viscosity of the oil. To enhance the production and optimise the process it is crucial to monitor the output of the mixture of water, oil and gas. The monitoring also helps to improve the operational and transportation management [1]. Water naturally occurs in the stratum and the percentage of water often increases with the production life of a well [2]. The water fraction also increases as the well is flooded with water. Many wells are still considered to be economic if the percentage of water in the liquid phase is more than 90% [3]. It is, therefore, important to consider the presence of water when predicting and designing a method to monitor flow behaviour in both pipelines and wells. In recent years, a numbers of studies have been published on water/oil/gas flow in pipes [4-7].

Conventionally, single phase monitoring techniques are utilised to measure the flow rates of well fluids by separating the mixture. The drawback is the time needed, which can take up to several hours, to obtain the flow rate of each well because each phase has to be separated before measuring it. The complexity of this technique increases when it comes down to monitoring up to 10 or more wells in the oil field which could be substantially time consuming and inconvenient. In addition, the oil-water-gas separators are expensive and maintenance-intensive [8].

One alternative to replace the water-oil-gas separators is the utilisation of Multiphase Flow (MPF) meters. It is acknowledged that MPF meters could bring benefits to the oil and gas industry in terms of layout of production facilities, reservoir management, regular monitoring, production allocation and well testing [9]. Ideally multiphase flow meter should be accurate, reliable, non-intrusive, compact and capable of measuring the flow rates continuously to within 5-10% of error [10]. Figure 1 shows the implementation of MPF meters in an offshore oil and gas production that involves several adjacent wells. The data captured during the production of these wells can help in estimating the performance of each individual well. The data gathered can also be used to locate a production anomaly, for instance, a gas or water breakthrough in the production well [11]. Conventional MPFs that employ phase separators create a complicated network of pipelines that occupy valuable space on the platform. Figures 2 and 3 show the single phase meter involving phase separators and an online multiphase flow measurement system respectively. The multiphase flow meter without phase separators can be installed and used in the same way as the test separator. It reduces and simplifies the piping as well as responding more rapidly to changes in the flowing phases of well fluids [12].

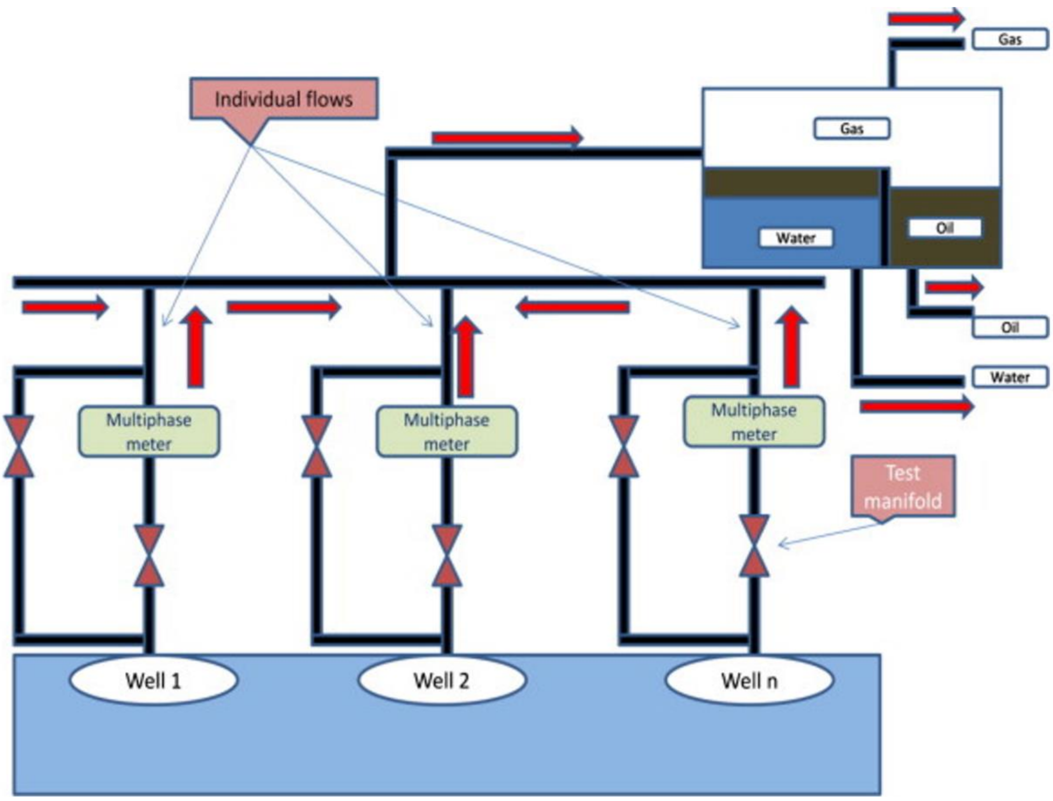

Figure 1: Schematic diagram of the implementation of multiphase flow meters in the adjacent wells to monitor the flow [11]

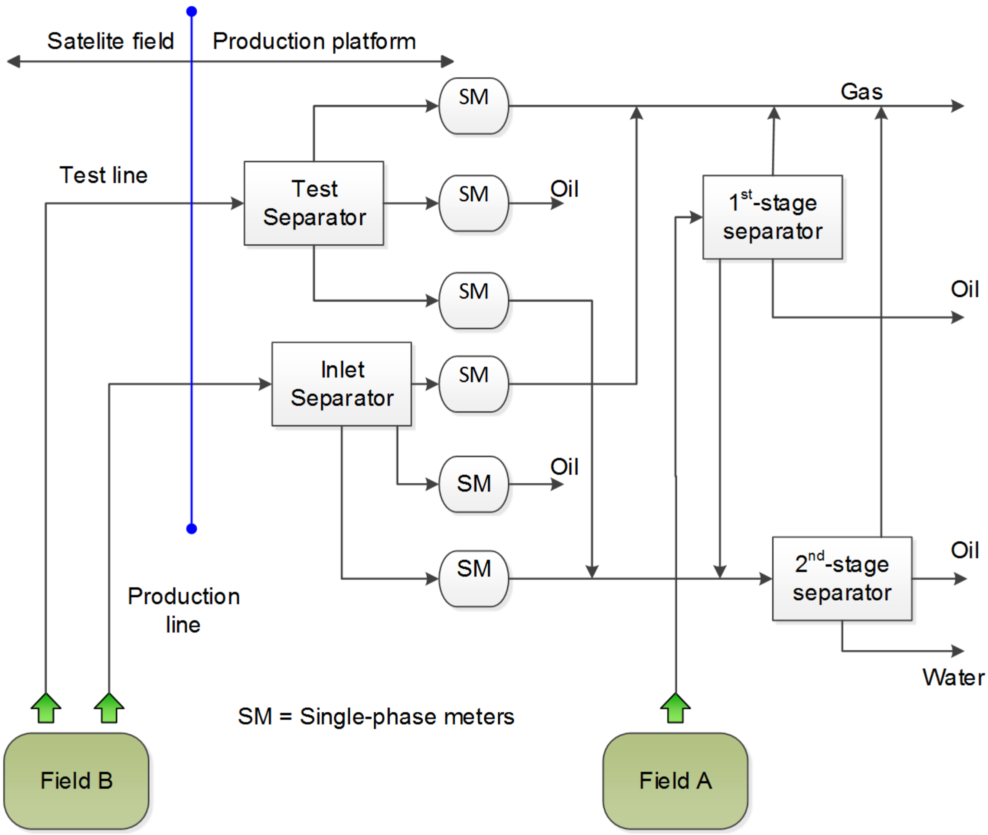

Figure 2: Conventional Multiphase flow measurement utilising phase separators [12]

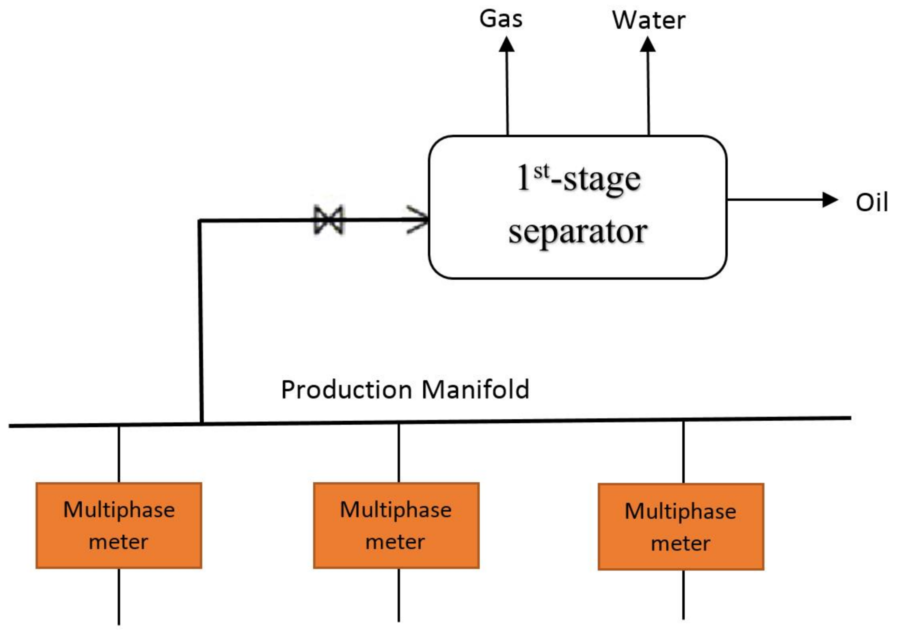

Figure 3: Online Multiphase flow measurement technique [12]

The current available MPF meters, however, are flow regime dependent [9, 13, 14]. Figure 4 shows four different flow regimes, i.e. homogeneous, elongated bubbles, stratified and wavy. Most of the MPF meters are calibrated for homogeneous flows. When the flow regime changes, significant errors occur as a result of the localised sensing path. Thus, these flow meters can only detect limited range of flow regimes (usually quasi-homogeneous or homogeneous flow) [13]. Independence to flow regime is important for the various designs of piping arrangements, for instance, incline or horizontal multiphase flow, this is due to the flow regimes, which tend to be stratified and are particularly difficult to measure using current MPF meters. Other challenges include changes in fluid properties and sensitivity of phase-fraction. Consequently, multiphase flow measurement is still an ongoing research topic, the objective is to enhance the robustness of the real time measurement of oil well streams, to provide a low-cost MPF meter solution and to continuously monitor the production of each oil well [15, 16].

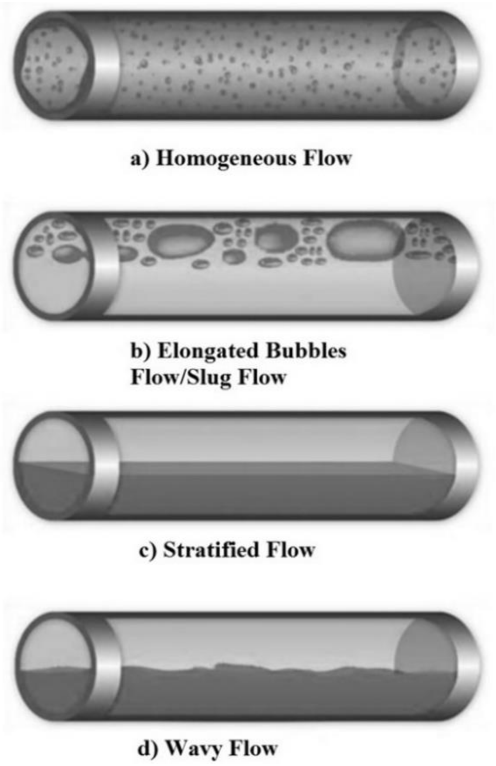

Figure 4: Different types of flow regimes [17]

Over the past two decades, many researchers have developed different measurement techniques to measure the extraction rates of oil and gas [9]. These include gamma-rays [18], microwave [10], impedance techniques [19] and tomography process [20], which are expensive and inaccurate [8]. The electric impedance technique relies on direct current method to measure the resistance of the fluid. The limitation of the impedance method is that this technique is only valid for low-loss fluids measurement [21]. The gamma-ray method has a stable performance, but the safety problem limits its application. Image reconstruction technique has also been developed utilising experimental optimisation such as simulated annealing and genetic algorithms. In comparison to other method; this technique offers substantial improvement in the reconstruction of quantitative images. Nevertheless, generally this technique is slow and expensive due to the great amount of iterations required for image reconstruction [22]. Linear reconstruction using linear back-projection algorithms can solve the huge iterations problem but since the algorithm was first introduced by Xie et al. [23] back in 1989 and then 1992, it lacks the mathematical support [23]. Magnetic induction tomography is a non-invasive imaging technique which interested in mapping passive electrical properties that are conductivity (σ), permittivity (ε) and permeability (μ) of a material. The drawback is the error for low conductivity material is pronounced [24]. To solve the above mentioned problems, microwave attenuation has been introduced; it is robust, cost effective and easy to be fabricated [25].

The research team at Radio Frequency & Microwave (RFM) Group of Liverpool John Moores University (LJMU) had previously attempted the use of Electromagnetic Wave (EMW) sensors for two-phase flow monitoring. Dykesteen et al. [21] did the similar study in year 1985 but it is only valid for homogeneous and low loss fluids. The previous research by Al-Kizwini studied the water-gas mixture using low EMW frequency between 240MHz and 330MHz. However, there were certain drawbacks in the study, these were:

- Low repeatability of the results.
- Lack of information on the temperature dependence.
- Lack of information on the monitoring of two phase fluid flows, i.e. water-air and oil-water.
- The antennas were in contact with water that may cause rust and error in measurements.

As mentioned, the above study by Al-Kizwini et al. [11] did not carry out temperature independent study and no repeatability was presented. The present research use high frequency (GHz region compared to MHz region) and demonstrates the repeatability along with temperature independent study which offer the extension and improvement to the previous research work.

This experimental study extended the work carried out by Al-Kizwini [11] to address the above aspects as well as to make the measurements more reliable, accurate and repeatable. An EMW cavity sensor was designed and used to measure the fractions of two phase water-air and oil-water stratified flows in the pipe. The outer cavity was left empty whereas the pipe inside was filled with the two phase fluids. To measure the former, i.e. water-air mixture, water was added in the pipe in various percentages to air. In the latter case, water in various percentages to oil was added in the pipe. Any scientific measurements and monitoring system requires to be reliable and repeatable. Hence, measurements were carried out at higher frequencies, more specifically in the microwave region, in contrast to [11] to address the repeatability. The measurements were also carried out at range of temperatures in the case of water-air phase system to study the impact of temperature change on the microwave measurements. It is important to mention that this study only focused on one type of flow, i.e. stratified. Further research work is needed to measure other flow types using this technique.

2. Microwave theory & methodology

The main principle of microwave analysis and monitoring is based on the material interaction with microwaves [26]. The broadband microwave analysis of the material can provide unique signal spectrums in the form of reflection coefficient (S_{11}) and transmission coefficient (S_{21}) based on the parameters such as conductivity and permittivity. Conductivity is defined as the material's ability to conduct electric current. Permittivity on the other hand is a complex value that measures the effect of a dielectric medium on the applied electric field. This is determined by the material's ability to polarise in response to the applied field and how the total electric field is reduced inside the material. These properties account for two main parameters, i.e. dielectric constant and dielectric loss of the material [27, 28].

i. ***Dielectric constant (ε'):*** When the EMW pass through the material, it causes the alternating polarisation inside the material. As a result, some of the energy is stored and the rest is being released slowly causing a reduction in the velocity of the wave. This phenomena helps in distinguishing materials with different dielectric constant values.

ii. ***Dielectric loss (ε''):*** It determines the reduction in the applied EMW's magnitude. The molecules under the influence of electric field rotates and produces friction causing the energy loss which reduces the magnitude of the wave.

Any change in the material's concentration, percentage, type, etc. will likely change its permittivity which causes the change in the microwave response when the material interacts with them. By measuring this response over the range of discreet frequencies the material can be characterised. Water, for example, is a polar molecule due to the charge separation that exists between the hydrogen and oxygen atoms. As a result, it has relatively high permittivity ($\varepsilon_r = 81$, at 15 °C). Hence, a small change in water fraction may result in comparatively large frequency shift. On the other hand, gases have low permittivity values approximately equal to ($\varepsilon_r = 1$). Non-polar materials such as oil have low permittivity value ($\sim\varepsilon_r = 2.2\ to\ 2.5$) [28, 29].

The EMW cavity resonates at certain frequencies depending on the dimensions of the cavity and permittivity of the material/fluid flowing through the cavity. Resonance occurs when an electric and magnetic fields forms a standing wave. Various combinations of standing waves may exist inside the cavity. It is therefore possible that various EMW modes can occur inside a particular cavity. The fundamental modes for cylindrical cavities are the TM_{010}, TE_{111} and TE_{011} modes. TM Mode (Transverse Magnetic) has an electric component in the propagation direction and TE Mode (Transverse Electric) has a magnetic component in the propagation direction. Each of these modes has its own resonant frequency, with a quality factor Q associated with it which is inversely proportional to the power dissipated in the cavity when an EMW oscillation is applied to it. The resonant frequency for a TM_{nm1} mode in a cylindrical cavity can be calculated using equation (1).

$$f_{nml} = \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\left[\left(\frac{p_{mn}}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2\right]^{1/2} \qquad (1)$$

where ε_r is the relative permittivity of the material, μ_r is the relative permeability of the material, c is the velocity of light, d is the depth of the cavity, p_{mn} is the mth root of the Bessel function of the nth order and b is the radius of the cavity.

Any number of antennae may be placed within the cavity for the purposes of transmission and reception of electromagnetic energy; however the most typical configurations involve one and two port (thus, one or two antennae) cavities. In a one port configuration it is possible, using a Vector Network Analyzer (VNA), to measure the power which is reflected back from the cavity as a result of microwaves interaction with the material; this is often referred to as an S_{11} parameter/signal. However, S_{11} measurements work best only for near field or close contact. In a two port configuration, the power is transmitted through the cavity, i.e. microwaves are inserted in the cavity to interact with the material and then received on the other end by a receiving antenna. The received signal is then forwarded to the VNA; this is referred to as an S_{21} parameter/signal. Since the material under test sits in the centre of the cavity, S_{21} is the better option [30].

In order to transmit the microwaves inside and to monitor its resonant behaviour a coupling structure or an antenna is required. The antenna should be relatively small to have least interaction with the fields inside. For the purpose of monitoring the S_{21} signal, a pair of loop antennae was used. Other options such as patch antenna won't be suitable as they can only measure the S_{11} (reflected signal), the results of which in the current study were not promising.

2.1. Microwave cavity and experimental setup

In this experimental study, the cylindrical cavity utilised had its diameter larger than the pipeline and is open at both ends. This design allowed the pipeline to appear continuous. The schematic diagram of the cavity along with the pipeline and the embedded coupling structures/antennae is shown in Figure 5. The non-intrusive design of the cavity allowed the antennae to be placed at the appropriate locations on the cavity. It also enabled the excitation of the resonant frequency for the analysis of water-air and oil-water fractions in the pipeline. The design of the cavity allowed the pipeline to be kept isolated and the antennae to be protected from the fluid. Although, the technique is robust and instantaneous, the limitation of this electromagnetic cavity sensor is that the pipe carrying the fluid should be none-conducive material to allow the penetration of microwaves through the pipe at higher frequencies.

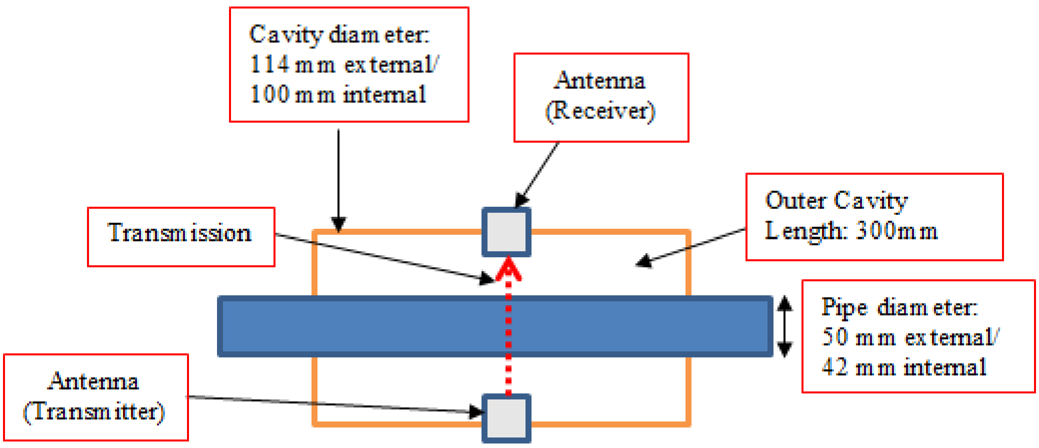

Figure 5: Schematic diagram of the resonant cavity with pipeline

The resonant cavity used is shown in Figure 6. It has an outer radius of 50 mm and a length of = 300 mm. The PVC pipeline inside the cavity has an outer radius of 25 mm. The outer cavity is made from brass. Antennae are attached to each side of the cavity as shown in Figure 6.

The non-intrusive design of the cavity enabled the outer pipe to be kept empty and the inner pipe filled with water-air and/or oil-water fractions. The mode at which measurements were taken only interacted with the central portion of the cavity where the PVC pipe sits and was sensitive to the permittivity changes in the pipe due to change in the fractions.

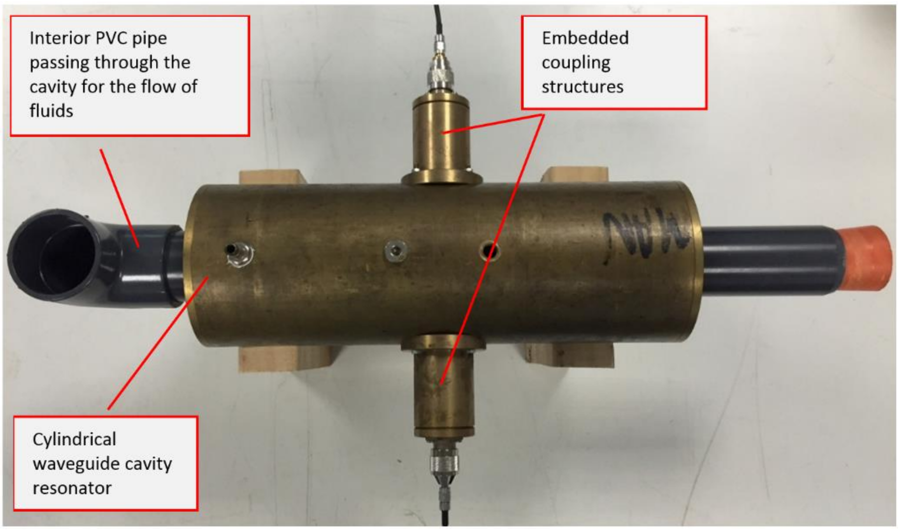

Figure 6: Cylindrical microwave cavity resonator with embedded antennas

The experimental setup of the measurement system is shown in Figure 7. The setup consists of Rodhe and Schwarz Vector Network Analyser (VNA) model ZVL-6 with a frequency range of 9 kHz -6 GHz, an online data processing computer with LabVIEW display to capture and analyse the data, the cylindrical resonant cavity along with loop antennae embedded on both sides, a PVC pipe passing through the cavity, cables and connectors. The input power used to launch the microwave inside the cavity was 0 dBm and 4000 data points were selected for each measurement.

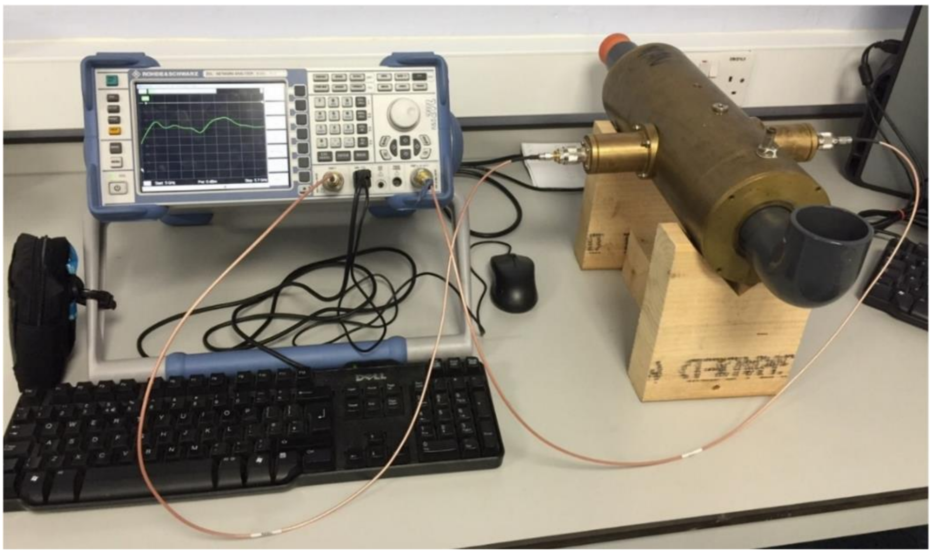

Figure 7: Experimental setup of the measurement system showing the cavity, VNA. LabVIEW display software, cables and connectors

2.2. Samples tested and measurements procedure

Three set of measurements were taken:

i) Measurements of percentage increase in the volume fraction of water to air.
ii) Measurements of percentage increase in the volume fraction of oil to water.
iii) Measurements of temperature dependence of the technique by analysing the water at various temperatures.

This is the initial phase of the research, thus only static water /air and water /oil were tested. The analysis of the temperature impact on water sample was used to establish and demonstrate the independence of the temperature of water on the microwave frequency response. The consistent output of this technique to the temperature change was useful to demonstrate the effectiveness of microwave analysis technique not only at the room but also at higher temperatures. This study could be extended further in the future work to include two phase fractions and the temperature impact on them. The samples analysed for the percentage of the volume fraction between Water-air and Oil-water is shown in Table 1. The sample of water tested along with the temperature change is shown in Table 2.

Table 1: List of two phase system of Air-water and oil-water tested for the monitoring and analysis of the volume fractions

Sample type	**Volume fraction (%)**		**Temperature (°C)**
	Air fraction	**Water fraction**	
Air-water (two phase)	0	100	20
	20	80	20
	40	60	20
	60	40	20
	80	20	20
	100	0	20
Sample type	**Oil fraction**	**Water fraction**	**Temperature (°C)**
Oil-water (two phase)	100	0	20
	80	20	20
	60	40	20
	40	60	20
	20	80	20
	0	100	20

Table 2: Analysis of the water sample to monitor the change in temperature and its impact on the microwave response frequency/amplitude

Sample type	**Volume fraction (%)**	**Temperature (°C)**
Water sample	100	28
	100	30
	100	41
	100	49
	100	58
	100	68
	100	74
	100	83

The sample of the fractions of water-air and oil-water were analysed at a constant room temperature of 20°C. This was maintained easily because the tests were carried out in a temperature controlled environment with a thermostat fitted in the room to constantly monitor and control the temperature. In the second test the water was boiled and poured into the pipe. The temperature of water was monitored and recorded using a laboratory thermometer.

The measurements of the change in the volume fraction of two phase systems was first conducted over the full range of spectrum between 9 kHz and 6 GHz. However, it was found that the frequency below 5 GHz did not correspond to the changes in percentage of water. The results of the frequency response were also not consistent with change in the fraction percentage. The frequencies above 5.7 GHz were eliminated because of the ambiguous microwave response as well as to avoid the multi modes and complexities in the data analysis in the later stage. The measurements were taken between 5-5.7 GHz with the cylindrical cavity operating in TE_{124} mode. The experimentation was conducted by measuring the volume fraction of water required to fill the PVC pipe that was equal to 740 ml. The volume was then divided by 5 to get the amount of volume fraction increase each time in the pipe which equaled to 148 ml. The measurement was first taken with the empty pipe, i.e. filled with 100% of air. Afterwards, as worked out, each 148ml of water was added into the pipe representing 20% increase in the water fraction and in proportion 20% decrease in the air fraction. The data was captured and recorded in real-time using LabVIEW program designed to display the microwave response curves. The percentage of the volume of water was increased from 0-100% in the pipeline. Likewise, similar procedure was repeated with oil-water volume fractions with oil starting at 0% and water at 100%, i.e. 740 ml. The percentage of water was decreased and oil increased by 20% and measurements taken for each of the percentage increase till the pipe was filled with 100% oil.

In the temperature dependent study of water, the pipe was filled with 100% of water at 83°C and the microwave response was captured and recorded. As the temperature dropped the resonant frequency was recorded. The interval of the data recording was set manually corresponding to the temperature drop (approximately every 10°C). The data recording can be set up at short intervals as per the industrial standard and the system can be modified accordingly for a real world problem. The data should be digitally controlled and recorded in such a case to enable real-time measurements. However, such a precise and digitally controlled data recording was not required in this experimental study as the data was captured for few of the temperature changes.

2.3. COMSOL Simulations

COMSOL 5.1 simulation package was used to simulate for the resonant frequency inside the cylindrical cavity. RF (Radio Frequency) physic was used the simulation. All the dimensions were drawn according to the experimental setup. The height of water level was calculated according the percentages utilized in the experiment. The frequency was set between 5-5.7 GHz with 100 points to reduce the amount of computational iterations.

3. Results and discussion

3.1. Microwave spectrum analysis of the results

Figure 8 shows the comparison of Air-water fractions as in Table 1 and discussed in the previous section. The highlighted section in the figure demonstrate a shift in the frequency and change in the amplitude of samples when the ratio of the volume fraction of Air decreases from 100-0% and water increase from 0-100%. Analysis of Figure 8 shows that:

- The frequency of the microwave response curve decreases and shifts to the left from 5.496 GHz to 5.470 GHz as the increase in the water fraction takes place in five steps of 20% each. It equates to a total shift of approximately 25.5 MHz. Keeping into consideration the sensitivity of the technique, the shift is significant.
- In addition to the frequency shift, a significant change in the amplitude was also observed as in Figure 8. The amplitude decreases as the percentage of the water increase and air decreases. The overall decrease in the amplitude from 100% air to 100% water is approximately -11.2789 dB.

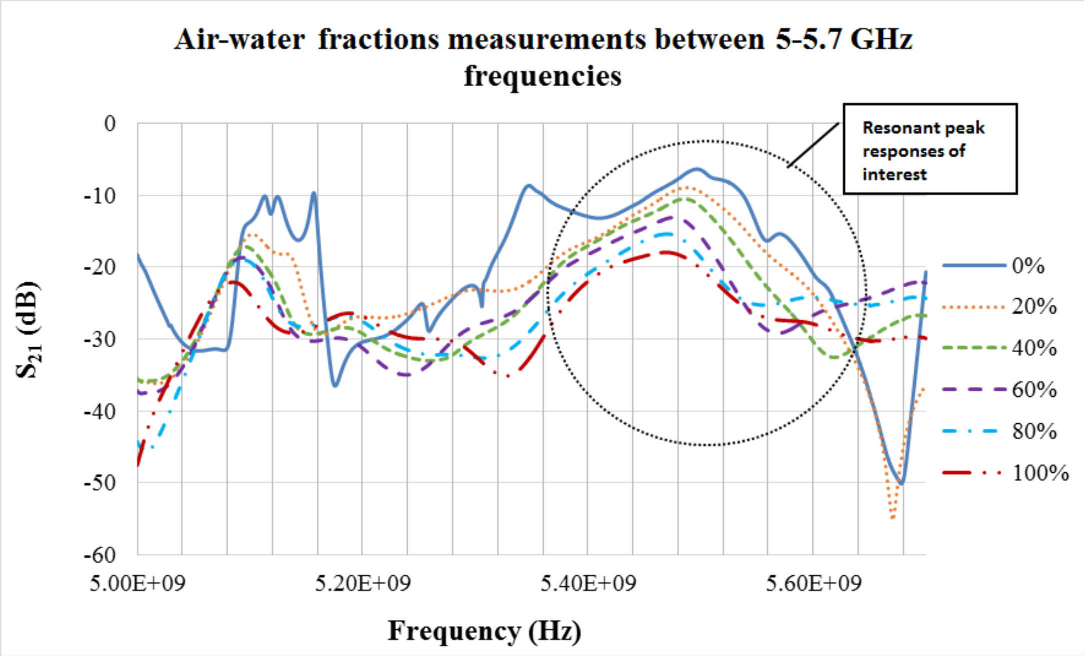

Figure 8: S_{21} (dB) measurements of the frequency response of air-water fractions using microwaves at 5-5.7 GHz

- Collectively it is demonstrated that both the shift in the frequency and change in the amplitude can be used to distinguish the increase/decrease in the volume fractions of water and gas in two phase flows.
- The results of the frequency shift and amplitude follow a specific pattern throughout the measurements showing the consistency of the microwave measurement technique.

The measurements in Figure 8 were repeated five times to check the consistency in the response pattern. The repetition of the measurements of fractions along with the standard deviation is presented in section 3.2.

A second set of measurements was carried out to monitor the change in the volume fraction of oil-water. The fractions of two phase fluid of oil-water analysed are shown in Table 1. The similar sample design was used whereby the measurements started with 100% of oil and 0% of water in the pipe. The ratio was then changed in 20% step changes with decreases in the oil and increases in the water up to the point where the whole pipe was filled with 100% of water with no oil left. The result of the measurements is shown in Figure 9. The highlighted area of Figure 9 demonstrates the same pattern as in Figure 8 whereby:

- A continuous shift in the frequency to the left (decrease) is observed when the percentage of water is increased and oil is decreased. The shift observed is from 5.504 GHz for 100% oil to 5.449 GHz for 100% water. This totals to a significant 54.6 MHz shift.
- As in Figure 8, the amplitude also changes from high to low with increases in the percentage of water fraction. The total decrease in the amplitude was recorded to be -10.562 dB.

- Both the amplitude change and frequency shift could be used to analyse and monitor the fraction percentage of the oil-air two phase systems. The results are very consistent in terms of changes in both the frequency and amplitude. The measurements were also repeated 5 times to check the accuracy and repeatability of the results.

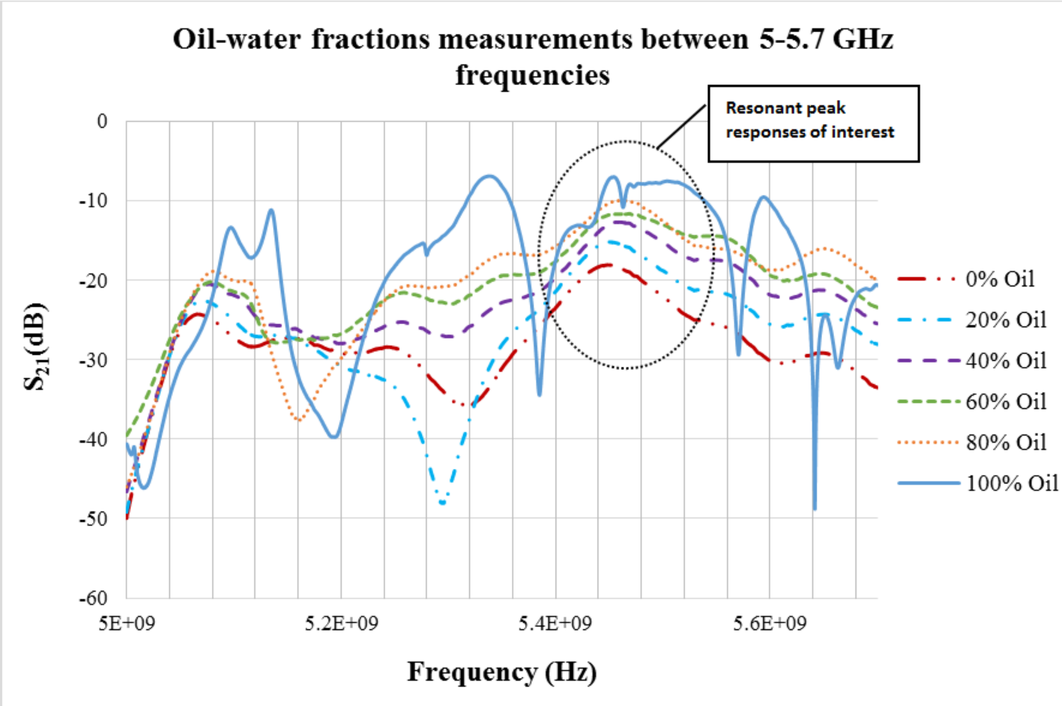

Figure 9: S_{21} (dB) measurements of the frequency response of oil-water fractions using microwaves at 5-5.7 GHz

It was also important to analyse the changes between each of the 20% fraction change of both air-water and oil-water flows. The frequency shift and amplitude change profile was plotted for each of the air-water and oil-water fractions and is shown in Figure 10. The results of the frequency plot in Figure 10 show that there is a measureable frequency shift for each of the fraction percent change. The frequency decreases when the water fraction increases to 100% in both air-water and oil-water two phase flows.

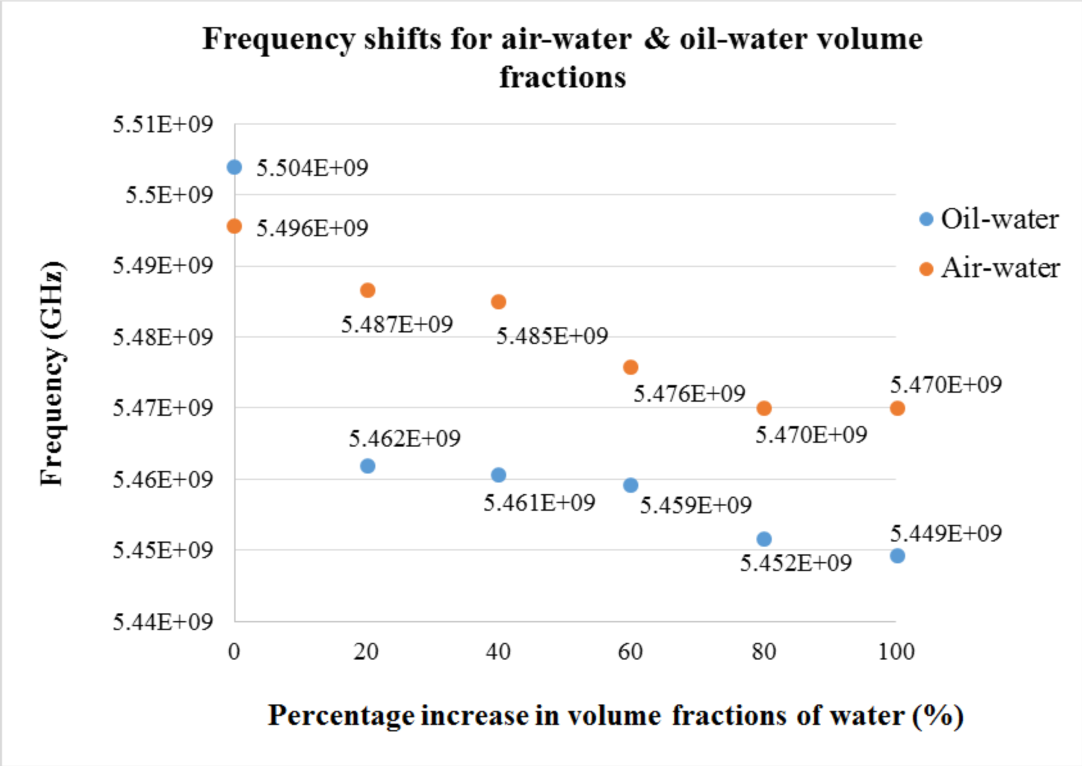

Figure 10: Graph of the frequency shift versus percentage increase in volume fractions of water

Figure 11 shows the COMSOL simulation 3D view of electric field inside the cylindrical cavity for 0% of water (filled with air) for illustration purpose.

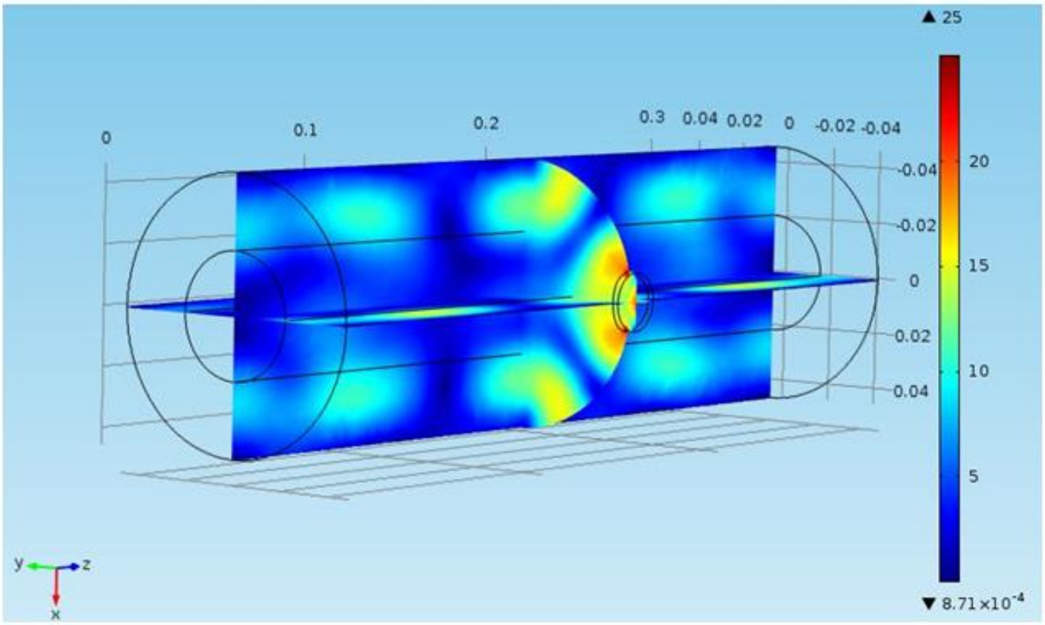

Figure 11: Electrical field intensity inside the cylindrical resonant cavity

Figure 12 shows the comparison between the experimental and simulation results. Only water/air fraction was simulated in this research to illustrate the accuracy of experimental analysis in comparison to the simulated results. The resonant frequency of each percentage of water from the experimental results was obtained and compared with the simulated results. Both the results show drop in frequency when the percentage of water increases.

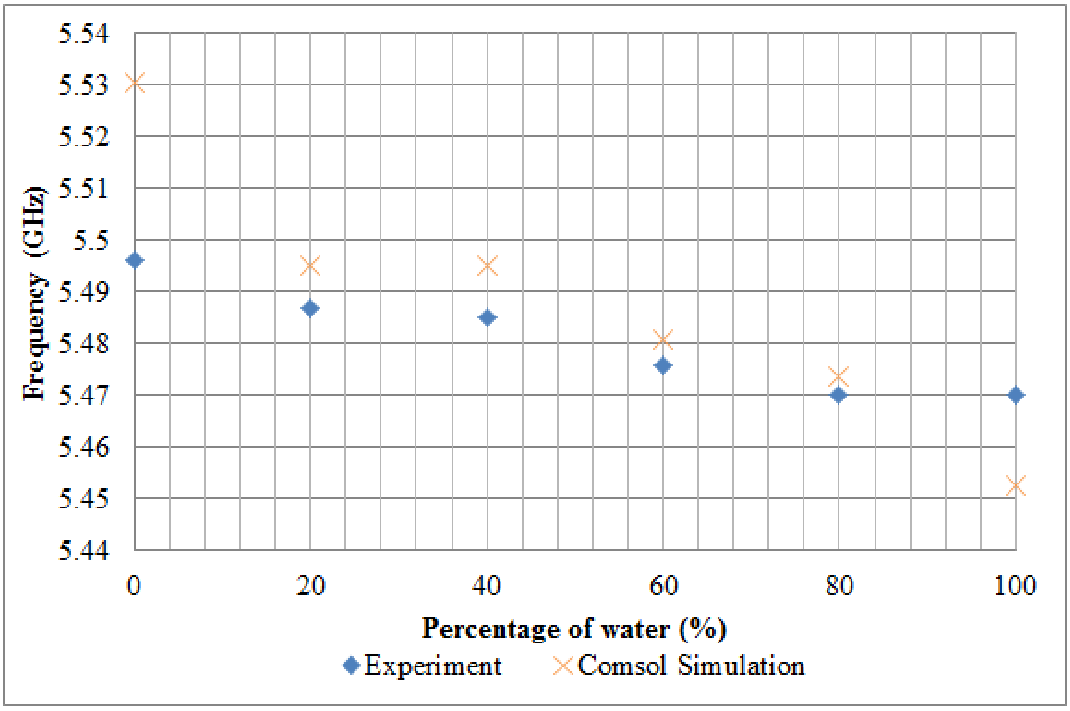

Figure 12: Comparison of the resonant frequency obtained from the experimental and simulation results

The third set of analysis was on water filled pipe to monitor if the change in temperature affects the microwave response curves. This was to monitor the temperature dependence of the microwave measurement technique. The results of the consistently decreasing temperature of water as listed in Table 2 are shown in Figure 13. Figure 13 shows the frequency and amplitude of 100% water in the pipe with different temperatures. It shows that no frequency shift is observed up to the temperature of 28°C. The temperature of the water was varied between 83 °C and 28 °C and this has been seen not affecting the accuracy of the system, despite the permittivity of water changing with the temperature. This is assumed to be due to the different overlapping modes negating the affect, as in adjacent frequency ranges if it is found that the affect is obvious. In order to prove the independence for two phase systems, further research work which is not covered in this article is required in the case of both air-water and oil-water two phase systems. It would also be interesting to study the temperature effect in multi/three phase flows.

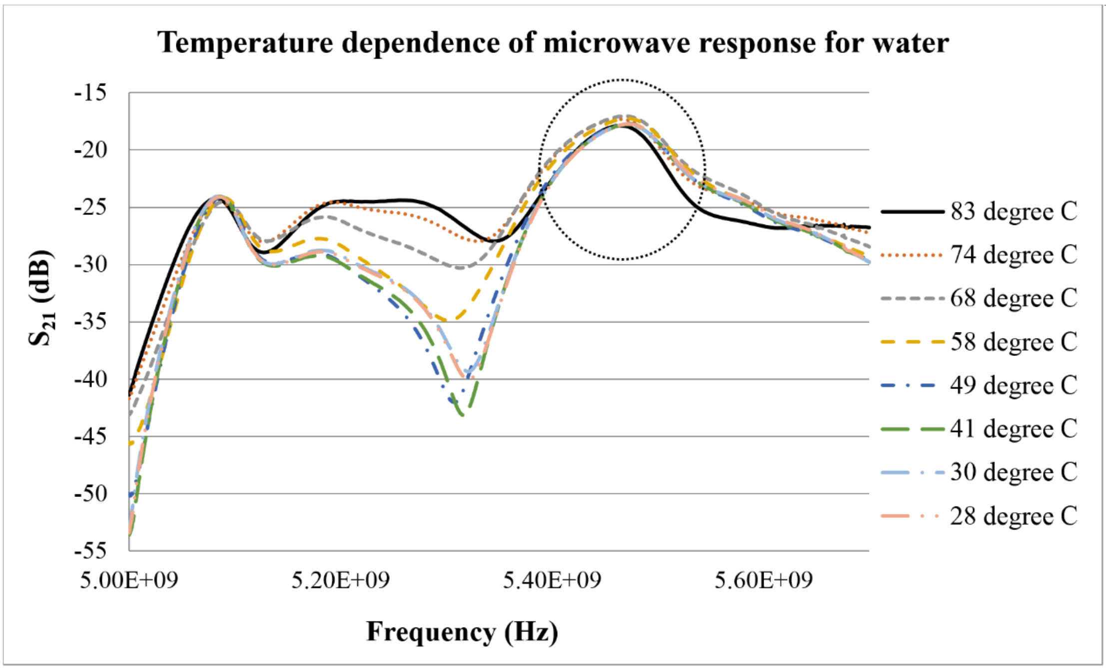

Figure 13: Graph of S_{21} (dB), showing the frequency at different temperatures for 100% water

3.2. Statistical analysis of repeatability and amplitude change

To address the repeatability, experimental measurements of both the air/water and oil/water fractions were repeated five times at different time. The data was then used to calculate the average amplitude and standard deviation as shown in Figure 14. The major errors are observed at 0% of water for oil/water and 100% of water for air/water. These errors may due to the air bubbles formed or trapped inside the oil or water when it is fully filled.

The output from the microwave responses in Figure 8 and 9 shows that the amplitudes obtained can be modeled accurately using a linear equation and could be presented as a function of change in the water fraction percentage. Figure 15 shows the linear relationship of the amplitude change to the fraction change of water in two phase system. It can be observed that the microwave signal amplitude decreases proportionally with the increase in the percentage of water. The plotted data shows a linear relationship between the volume fraction of water and amplitude of microwave signal captured.

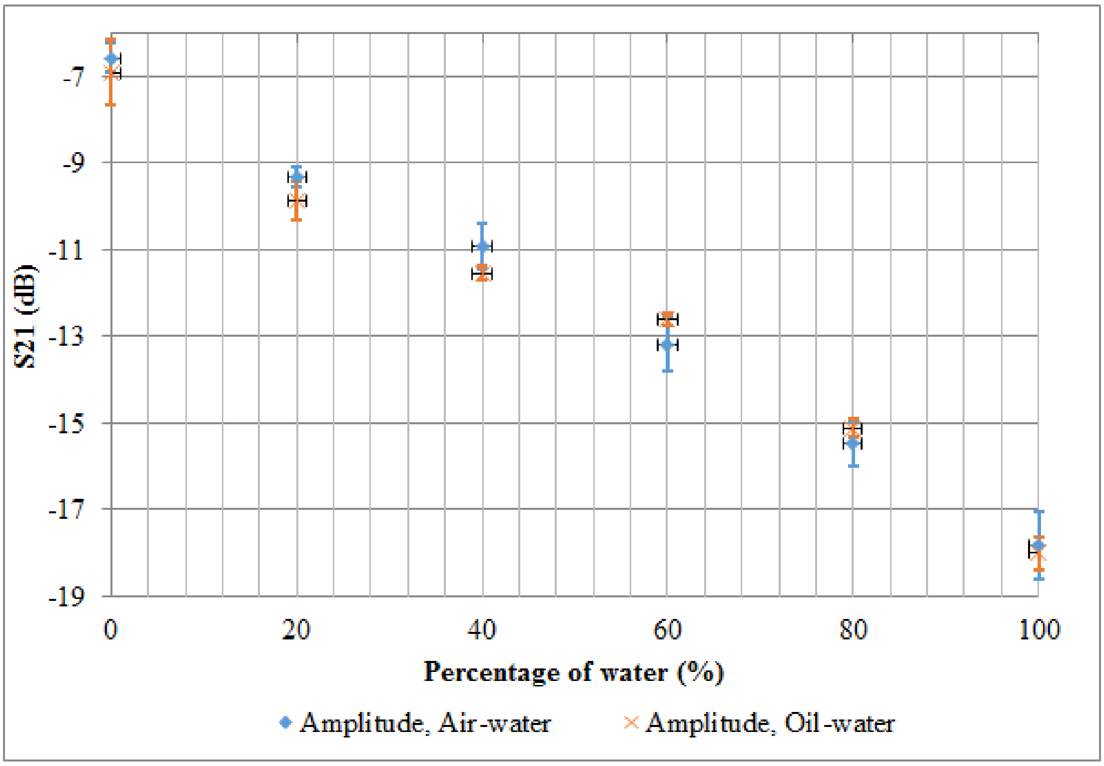

Figure 14: Average amplitude for each of the water/air and water/oil percentage with standard deviation error bars

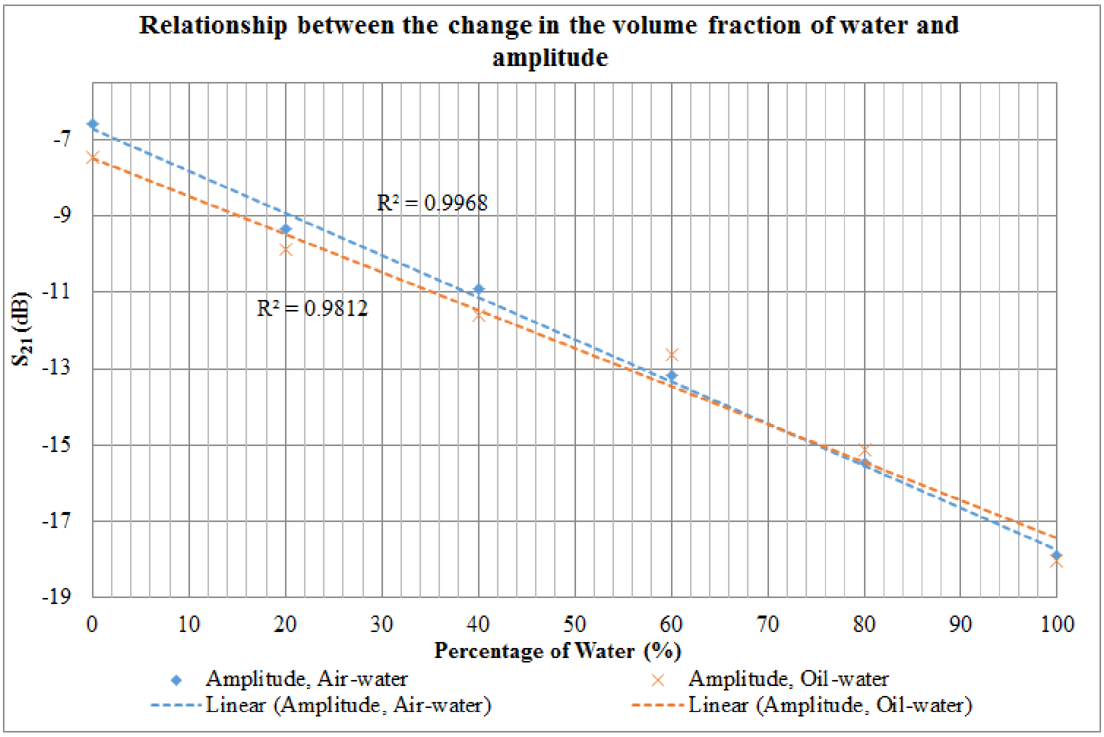

Figure 15: Relationship between the change in the volume fraction of water and amplitude in two phase systems

4. Conclusions & recommendations

The electromagnetic waves ranging from 5 GHz to 5.7 GHz was used to analyse one and two phase stratified flow systems of water, air-water and oil-water in a pipeline. The change in the permittivity of the fluids was used to differentiate between the changing volume fractions of air, water and oil. The results were presented in the form of frequency shift and amplitude change graphs. The following are some of the conclusions from the investigation:

- Measureable resonant frequency shifts were observed in the case of both the air/water and oil/water fractions of various percentages (Figure 8, 9, 10). A common phenomena was a shift to the right with a decrease in the water percentage in the fractions. This showed a decrease in the dielectric properties of the mix.
- There was a prominent change in the amplitude in the case of both the air/water (Figure 8) and oil/water (Figure 9) fractions. From the results, reduction in the amplitude can be linked to the increase in the water fraction percentage in proportion to both the air and oil. Since, water is “lossy” in nature, the experimental results obtained supported this theoretical fact. Based on the interaction behaviour of lossy mediums with microwaves, similar behaviour can be expected for other liquid/gas combination. An experimental verification, however, would be required.
- An in depth analysis of the repeatability of the measurement results was also conducted. The five times measurements of each of the air/water and oil/water fractions was averaged and standard deviation calculated. It can be observed from the results in Figure 14 that a slightly higher error was noticed at 0% and 100% water fraction in the mix. This could be attributed to the instrumentation and measurement error. However, most of the response of microwaves to the material (mix) was consistent. The accuracy presented in the measurement technique shows that it can be further developed for industrial scale analysis.
- A linear fit of the response of the microwave interaction with the air/water and oil water fractions showed that each of the 20% change in the water fractions can be modelled accurately and predicted if required. This could be helpful in the further development of the sensor system and intelligent analysis software tool to predict and detect in real-time various types of two phase air/water and oil/water fractions.
- In the case of temperature dependent study of water, the results were promising with no shift in the resonant peak observed with temperature decrease. This potentially shows the independence of the microwave measurement technique despite the changing permittivity of water when heated. It is important in terms of the industrial applications because the measurements could be carried out in real-time without the two phase mix dependence on the important factors such as temperature. This however needs to be verified for smaller changes in the temperature through a temperature controlled data recording tool. The temperature dependence also need to be verified for the three phase systems and more complex percentages of mix.

On the basis of this experimental study, further improvements, experimentation and design work is required. Hence, it is recommended that:

- This study is proposed to be extended further to demonstrate the effectiveness of microwave sensing techniques in the analysis of other type of flows such as homogeneous, wavy and elongated bubbles flow. This will build a substantial evidence to demonstrate the suitability of using microwave sensors in the analysis of two phase systems. It will also be able to demonstrate that microwave sensors based on the principle of changing permittivity can replace conventional measurement techniques.
- A detailed temperature study of both the two phase and three phase systems is required. This is to evidence the temperature dependence of the technique as well as to verify the claim made in this research work. The can also include fractions in various uneven percentages to replicate the real-world conditions where the percentages of the water/air/oil can vary in the mix.
- An intelligent software system is recommended to be built in the future study. The database would capture all the spectra to match the measurements in later stage and to verify the accuracy, repeatability and versatility of the sensing system.
- A new cavity is proposed to be built to address the limitations in the current study in terms of measurements and to remove any anomalies and errors in the measurements. It is also important to relate more complex properties of the two/three phase fractions to the spectra obtained. In the case of a flowing liquid-gas mixture, a straight stretch of pipe would be needed to avoid uncontrolled disturbances to the flow pattern.

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References

[1] S. Al-Hejeri, S.R. Wylie, A. Shaw, A.I. Al-Shamma'a, Real Time EM waves monitoring system for oil industry three phase flow measurement, Journal of Physics: Conference Series 178, (2009).

[2] X.-X. Xu, Study on oil–water two-phase flow in horizontal pipelines, Journal of Petroleum Science and Engineering, 59(2007) 43-58.

[3] G.F. Hewitt, Gas-liquid-liquid: a pahse too far?, BHR Group, Multiphase '97, (1997) 215-35.

[4] M.S. de Castro, C.C. Pereira, J.N. dos Santos, O.M.H. Rodriguez, Geometrical and kinematic properties of interfacial waves in stratified oil–water flow in inclined pipe, Experimental Thermal and Fluid Science, 37(2012) 171-8.

[5] J.-y. Xu, Y.-x. Wu, F.-f. Feng, Y. Chang, D.-h. Li, Experimental investigation on the slip between oil and water in horizontal pipes, Experimental Thermal and Fluid Science, 33(2008) 178-83.

[6] O.M.H. Rodriguez, R.V.A. Oliemans, Experimental study on oil–water flow in horizontal and slightly inclined pipes, International Journal of Multiphase Flow, 32(2006) 323-43.

[7] J. Hapanowicz, Slip between the phases in two-phase water–oil flow in a horizontal pipe, International Journal of Multiphase Flow, 34(2008) 559-66.

[8] H. Wang, G.H. Priestman, S.B.M. Beck, R.F. Boucher, A remote measuring flow meter for petroleum and other industrial applications, Measurement Science and Technology, 9(1998) 779.

[9] R. Thorn, G.A. Johansen, E.A. Hammer, Recent developments in three-phase flow measurement Measurement Science and Technology, 8(1997) 691-701.

[10] S.L. Ashton, N.G. Cutmore, G.J. Roach, J.S. Watt, H.W. Zastawny, A.J. McEwan, Development and trial of microwave techniques for measurement of multiphase flow of oil, water and gas, SPE Asia Pacific Oil and Gas Conference, Melbourne, Australia, 1994.

[11] M.A. Al-Kizwini, S.R. Wylie, D.A. Al-Khafaji, A.I. Al-Shamma'a, The monitoring of the two phase flow-annular flow type regime using microwave sensor technique, Measurement, 46(2013) 45-51.

[12] J. Amdal, H. Danielsen, E. Dykesteen, D. Flolo, J. Grendstal, H.O. Hide, et al., Handbook of Multiphase Metering. , 2004.

[13] E.A. Hammer, G.A. Johansen, Process tomography in the oil industry - State of the art and future possibilities, Measurement and Control, 30(1997) 212-6.

[14] A. Plaskowski, M.S. Beck, R. Thorn, T. Dyakowski, Imaging Industrial Flows: Applications of Electrical Process Tomography, UK: Institute of Physics Publishing; 1995.

[15] Y. Li, W. Yang, C.-g. Xie, S. Huang, Z. Wu, D. Tsamakis, et al., Gas/oil/water flow measurement by electrical capacitance tomography, Measurement Science and Technology, 24(2013) 074001.

[16] L. Yi, Y. Wuqiang, W. Zhipeng, D. Tsamakis, X. Chenggang, H. Songming, et al., Gas/oil/water flow measurement by electrical capacitance tomography, IEEE International Conference on Imaging Systems and Techniques (IST), 2012, pp. 83-8.

[17] I. Ismail, J.C. Gamio, S.F.A. Bukhari, W.Q. Yang, Tomography for multi-phase flow measurement in the oil industry, Flow Measurement and Instrumentation, 16(2005) 145-55.

[18] G.J. Roach, J.S. Watt, Current status of development of the CSIRO gamma-ray multiphase flow meter, 14th North Sea Flow Measurement Workshop, Peebles, Scotland, 1996, pp. 1-11.

[19] E. Dykesteen, A. Hallanger, E. Hammer, E. Samnoy, R. Thorn, Non-intrusive three-component ratio measurement using an impedance sensor, Journal of Physics E: Scientific Instruments, 18(1985) 540-4.

[20] Y.A. Wahab, R.A. Rahim, M.H.F. Rahiman, S.R.Aw, F.R.M. Yunus, C.L. Goh, H.A. Rahim, L.P. Ling, Non-Invasive process tomography in chemical mixture-a review, Sensors and Actuators B: Chemical, 210(2015) 602-17.

[21] E. Dykesteen, A. Hallanger, E. Hammer, E. Samnoy, R. Thorn, Non-intrusive three-component ratio measurement using an impedance sensor, Journal of Physics E: Scientific Instruments, 18(1985) 540-44.

[22] C. Ortiz-Alemán, R. Martin, J.C. Gamio, A. Nicolas, Application of Simulated Annealing and Genetic Algorithms to the Reconstruction of Electrical Permittivity Images in Capacitance Tomography, 3rd World Congress on Industrial Process Tomography, Banff, Canada, 2003, pp. 794-9.

[23] J.C. Gamio, C. Ortiz-Aleman, R. Martin, Electrical capacitance tomography two-phase oil-gas pipe flow imaging by the linear back-projection algorithm, Geofisica International, 44(2005) 265-273.

[24] Z. Zakaria, N.A.M. Zain, I. Balkis, S. Yaakob, M.S.B. Mansor, R.A. Rahim, N.M.N. Ayob, Evaluation of square type electromagnetic field screen implementation on interference effects in magnetic induction tomography modality, IEEE Sensors 2012, Taipei, Taiwan, 2012, pp. 1-4.

[25] Z. Qu, Q. Zhao, Y. Meng, Online measurement of water concentration of oil–water mixtures in the flow of pipeline by using eddy current method, Measurement Science and Technology, 24(2013) 125304.

[26] S.G. Bjarnadottir, K. Lunde, O. Alvseike, A. Mason, A.I. Al-Shamma'a, Assessing quality parameters in dry-cured ham using microwave spectroscopy, Meat Science, 108(2015) 109-14.

[27] M. Ateeq, S. Wylie, A. Al-Shamma'a, H. Al-Nageim, Microwave spectroscopy: a potential technique to analyse bitumen dielectric and physical properties, Measurement Science and Technology, 23(2012) 13pp.

[28] A. Mason, S. Wylie, O. Korostynska, L.E. Cordova-Lopez, A.I. Al-Shamma'a, Flexible e-textile sensors for real-time health monitoring at microwave frequencies, International Journal on Smart Sensing and Intelligent Systems, 7(2014) 32-47.

[29] S.R. Wylie, A. Shaw, A.I. Al-Shamma'a, RF sensor for multiphase flow measurement through an oil pipeline, Measurement Science and Technology, 17(2006) 2141.

[30] A. Mason, B. Abdullah, M. Muradov, O. Korostynska, A. Al-Shamma'a, S.G. Bjarnadottir, K. Lunde, O. Alvseike, Theoritical basis and application for measuring pork loin drip loss using microwave spectroscopy, Sensors 16(2016) 1-13.