Detection of the gas–liquid two-phase flow regimes using non-intrusive microwave cylindrical cavity sensor

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Abstract:

Gas-liquid two-phase flow phenomenon occurs in various engineering applications and the measurement of it is important. A microwave sensor in the form of a cylindrical cavity has been designed to operate between 5 to 5.7GHz. The aim is to analyse a two phase gas-liquid flow regime in a pipeline. LabVIEW software is utilised to capture the data, process it and display the results in real time. The results have shown that the microwave sensor has successfully detected the two phase flow regimes in both the static and dynamic flow environments with reasonable accuracy. The study has also shown the independence of the technique and its accuracy to the temperature change (28-83°C). Several flow regimes of the gas-liquid two-phase flow have been discussed. The system is also able to detect the stratified, wavy, elongated bubbles and homogeneous flow regimes.

Keywords: flow regime, cavity, microwave sensor, electromagnetic wave, water fraction

1. Introduction

Two-phase flows are commonly encountered in various engineering applications such as chemical industry, heat exchangers, oil and gas industry, rocketry, nuclear engineering, food production, etc. to name a few [1, 2]. Out of these, the gas-liquid flow is one of the most common and the most complex types of flow. As the interaction takes place between the gas and the liquid during the flow process, the distribution and the shape of the interface of two-phase flow changes [3]. The characterisation of the behavior of gas-liquid flow is very important for the sake of understanding the measurements as well as the chemical processes associated with it. Thus, multiphase flow measurement before processing within the pipeline for the purpose of production is essential for safety and efficiency [4]. Over the past two decades, many researchers have developed different methods of measuring the rates of production of oil and gas phases. These methods include multiphase flow meters (MPF), microwave [5, 6], γ-ray method [7], tomography process [8, 9] and impedance techniques [10]. However, most of these methods have certain disadvantages which make them unsuitable for the industrial use. These include the methods being inaccurate as well as significantly expensive to develop and implement [11, 12].

A flow regime is heavily influenced by the thermal dynamic equilibrium and the mechanical interaction between the phases. These two properties are dependent on the parameters such as the flow conditions (temperature and pressure), the channel geometry, the phase's superficial velocity, the flow direction (descending, ascending, parallel and counter flow) and the fluid properties (surface tension, viscosity and density). A complete classification of the flow patterns operating conditions and the associated pipe geometries are summarised by Thome [13] and Rouhani and Sohal [14]. Figure 1 shows an example of the stratified, wavy, elongated bubbles/slug and homogeneous/dispersed bubbles flow. Flow regime dependence is a major problem for most of the commercially available multiphase flow meters (MPFM) [16-18]. For example, Figure 2 shows three different types of gas-oil flow regimes (stratified, annular and homogeneous) each with a 25% oil fraction by volume. Current MPFMs provide inaccurate measurements when the flow regime changes and it will have a significant error as a result of the localised sensing path.

Thus, these flow meters can only detect certain types of flow regimes (typically a homogeneous or a quasi-homogeneous flow). Independence to the flow regime is important for various piping arrangements and designs, for instance, in the case of an inclined or horizontal multiphase flow. This is because flow regimes such as stratified flow, etc. are particularly difficult to measure using the current MPF meters [17]. To reduce the metering errors of the two-phase flow, additional correcting methods are also needed [19].

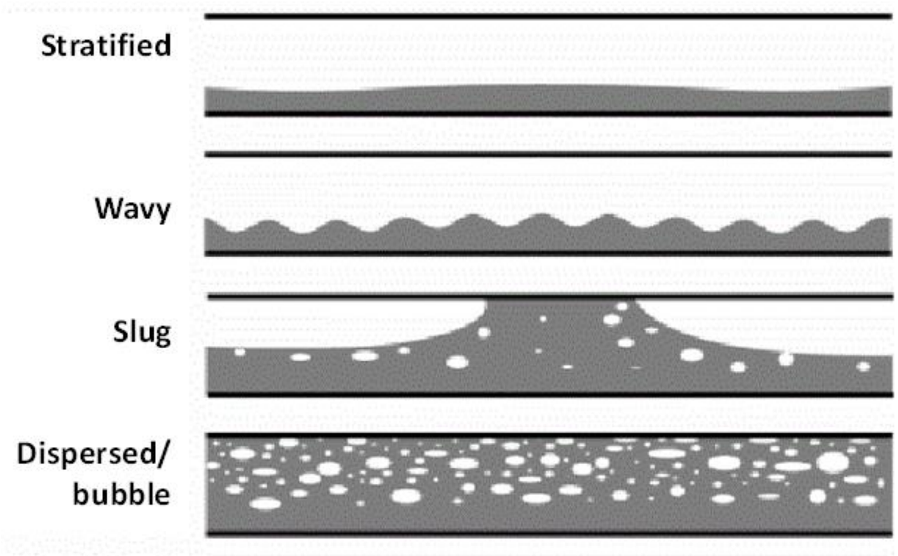

Figure 1: Pictorial representation of different flow regimes [15]

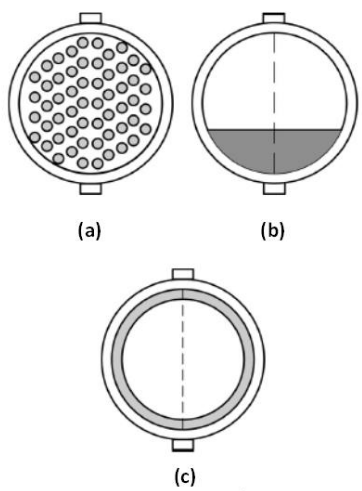

Figure 2: Different type of flow regimes (real oil concentration = 25%) (a) Homogeneous flow (b) Stratified flow (c) Annular flow [20]

It is crucial to measure the gas-liquid fraction, the water-in-liquid ratio and phase velocities in order to acquire the extraction flow rates [21]. Several MPFMs have been designed and developed for this purpose by companies and research organisations, utilising various measurement technologies. Although those MPFMs are commercially available, number of challenging problems are yet to be solved, for instance, different flow regimes, change in the fluid properties and sensitivity of the phase-fraction. Consequently, many researchers are still involved in researching multiphase flow measurement techniques

Al-Kizwini [22] had previously studied the gas-water mixture using the low Electromagnetic (EM) wave frequency range. He attempted to use the frequency between 240 MHz and 330 MHz. However, certain parameters such as the dependence of the measurements on changing temperature, repeatability and accuracy, flow rates, etc. were ignored. Also, all the tests carried out were on the gas-water fractions in their static state. No physical (dynamic) flow was introduced in the study. The study was only focused around detecting the change in the microwave response with the percentage of water fraction.

This paper has substantially extended the work previously carried out by Al-Kizwini. The experimental study discussed the use of a microwave cavity sensor to measure the fractions of two phase gas-water flow in the pipe. The measurements were carried out both in the static (no flow in place) and dynamic conditions, i.e. while the gas-water fraction was physically flowing. All the measurements were carried out at a higher frequency range of 5-5.7 GHz in contrast to Al-Kizwini for accurate, consistent and robust measurements. The outer cavity was filled with air and the water was allowed to flow in the pipe inside the cavity without disturbance. Measurements were also carried out to study the impact of temperature change on the measurement technique.

Microwave based sensing is a non-ionising technique utilising a low power input and has a good penetration depth.

2. Microwave sensor operating theory

Different phases in the pipeline have different electrical permittivity values. Changes in the phase concentration, type, percentage, etc. will likely change its permittivity. Microwaves utilise the change in the permittivity to measure the volume fraction of a multiphase flow in a pipeline. On its interaction with the material, the response of microwaves to the material can be collected through a unique set of signal spectrums known as the reflection co-efficient (S_{11}) and the transmission co-efficient (S_{21}). These are related to the conductivity and the electric permittivity of the material. The electric permittivity ε_r is a complex quantity and measures the ability of a dielectric material to be polarised by an electric field. It varies with the frequency and is expressed in the form of both the energy stored by the material (a dielectric constant, ε'_r) and any losses of the energy (a dielectric loss, ε''_r) which might occur [23].

(1) *Dielectric constant:* When microwaves interact with the material, they causes an 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 phenomenon helps in distinguishing materials with different dielectric constant values.

(2) *Dielectric loss:* determines the reduction in the microwaves magnitude. Microwaves when passing through the material causes the molecules under the influence of an electric field to rotate and produce friction. This results in the energy loss and hence reduces the magnitude of the wave.

Due to the charge separation between the hydrogen and oxygen atoms, water is termed as a polar molecule. It has therefore a relatively high permittivity ($\varepsilon_r = 81$, at 15 °C) in contrast to that of the air that has a low permittivity ($\varepsilon_r = 1$). Non-polar materials such as oil on the other hand has low permittivity ($\varepsilon_r =$ 2.2-2.5). Permittivity of the material can be determined by measuring the resonant frequency inside an electromagnetic wave cavity [12]. A cylindrical cavity is simple to fabricate and consists of a metallic wall with metallic circular ends. In order to measure the resonant behavior inside the cavity, coupling structures/antennas are required to interact with the field inside the cavity. The antennas should be relatively small to avoid their effect on the fields they are measuring. The antennas are typically either monopoles or loops. The fundamental modes for cylindrical cavities are the TM_{010}, TE_{111} and TE_{011} modes. TM (Transverse Magnetic) Mode has an electric component in the propagation direction and TE (Transverse Electric) Mode has a magnetic component in the propagation direction. Each mode generates its own resonant frequency with a quality factor (Q) associated with it and is inversely proportional to the power dissipated in the cavity for each of the applied EM wave oscillation. The resonant frequency for a

TM_{nm1} mode in a cylindrical cavity can be calculated using an equation (1).

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

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

3. Methodology

In this research work, the microwave sensor was designed such that the sensor's cavity was larger in diameter than the PVC pipe running through it and was open at both ends. This design allowed the liquid to flow continuously without any interruption as shown in Figure 3. This none-intrusive design allowed the coupling structures to be separate from the pipeline and the flowing liquid. The sensor's cavity was made out of brass. Being electrically conductive, the cavity was used to create the resonant modes when the microwaves were inserted into the cavity. The design also allowed the pipeline to be clean, with the cavity and antennas in place and protected from the flowing liquid.

The measurements were carried out by capturing the S_{21} parameter for each of the gas-water fractions. The data was captured to measure the percentage change in the gas-water fraction, influence of the temperature change on the measurement technique, static and dynamic flow conditions as well as different types of flows. A resonant peak was obtained representing the response of the gas-water fraction to the applied microwaves. In addition to measuring the resonant peaks, the change in the amplitude of the signal with change in the temperature, water fraction, flow type and rate was also observed. Both the resonant peaks and change in the amplitudes were used to represent the above set of measurement parameters. In addition, statistical analysis was also carried out to model the change in the S_{21} with change in the water fraction.

3.1. Prototype and the real time monitoring

The microwave cavity sensor set up is shown in Fig. 4. This experimental study used the Rodhe & Schwarz Vector Network Analyzer, VNA (ZVL 9-13.6 GHz), an online data processing software system (LabVIEW display), the microwave cavity sensor, a PVC pipe and coupling structures (loop antennas to transmit and receive microwave signals) embedded inside the cavity. The experiments were conducted by measuring the volume of water filled in the pipe that was found to be 740ml. The total volume was then divided by 5 to calculate each of the 20% increase in the water fraction, which equaled to 148ml. Each of the measurements was recorded by adding 148ml of water into the pipe representing 20% increase in the water fraction. The data was captured and processed in real time during the experiment. The percentage volume of the gas-water fraction was increased in this manner from 0-100% in the PVC pipe.

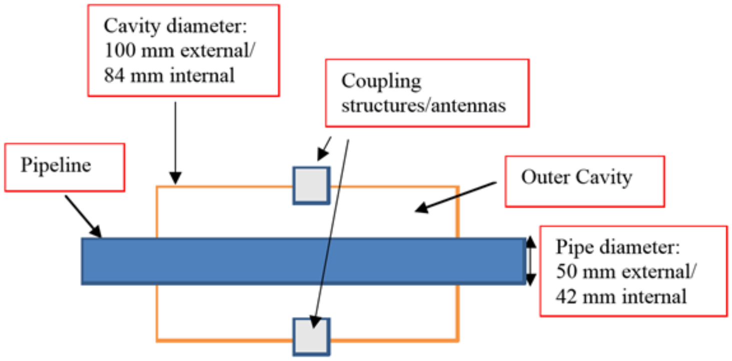

Figure 3: Schematic representation of the cavity sensor along with the coupling structures

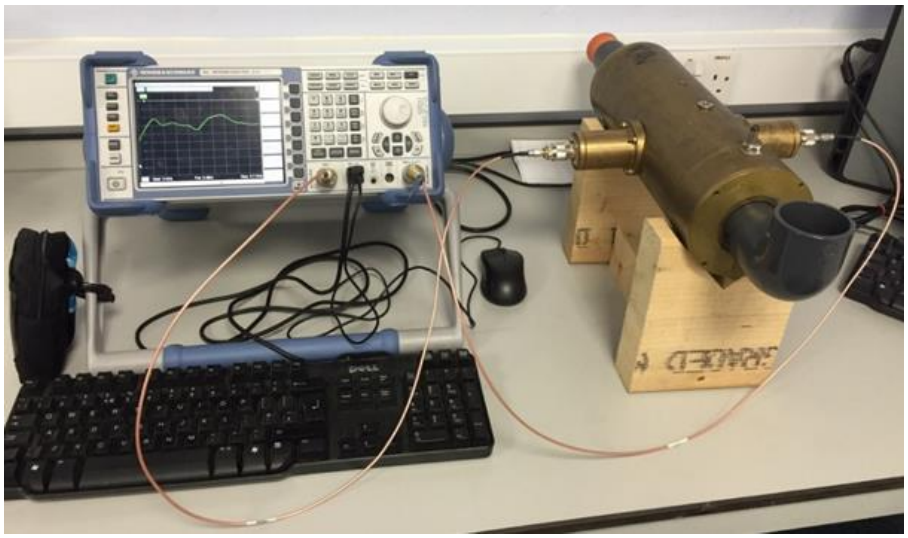

Figure 4: Experimental setup of the Microwave cavity sensor

3.2. Two-phase flow experiments

To visualize the flow before entering, and, after coming out of the cavity sensor, acrylic pipe was connected to both ends of the PVC pipe. The diameter of the pipe was 50mm. The whole setup for the flow measurements consisted of the water tank, cavity sensor, PVC pipe, acrylic pipe, air pump, flow meter and a pump. The Linear equation derived from the maximum amplitudes is introduced in the Labview software to record, calculate and display the result (percentage of water) in real time. The setup is shown in Figure 5. A transparent ruler was used to measure the percentage of water flowing through the cavity sensor for the stratified flow as shown in Figure 6. Table I shows the calculated height of the water inside the transparent acrylic pipe before entering the cavity sensor. The water and the air flow rate were varied to create different flow regimes. Figure 7 shows the schematic representation of the two phase flow experiment.

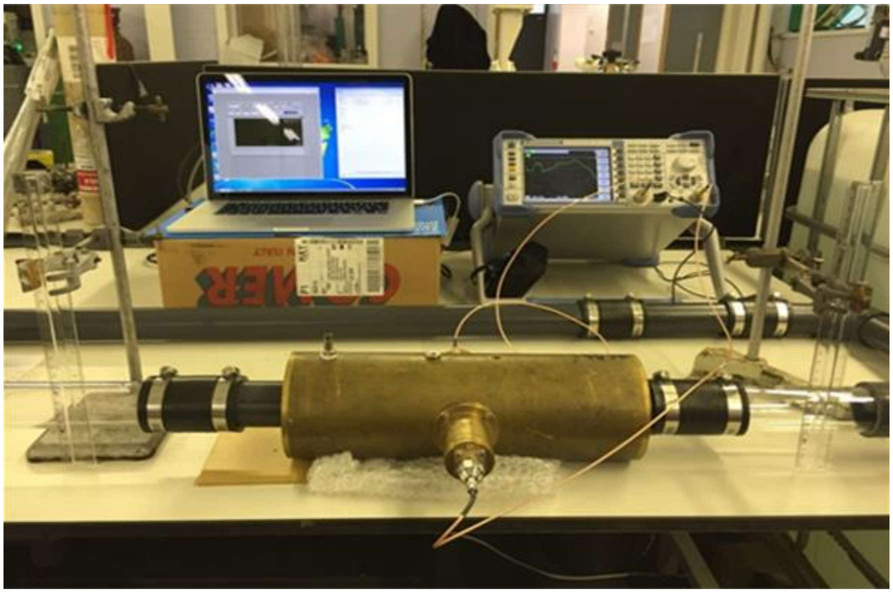

Figure 5: Experimental setup of the two-phase flow sensor measurement system

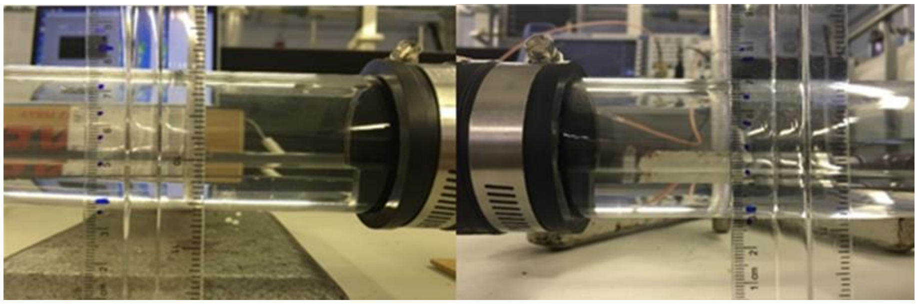

Figure 6: Representation of the use of transparent ruler to measure the percentage of water flowing through the pipe and the cavity sensor

3.3. Study of the temperature independence to the microwave measurements

In this study, the pipe was filled 100% with the boiling water. As the temperature dropped, the microwave response of the temperature change was recorded between 5-5.7 GHz. The data was captured manually every 5 to 10 minutes corresponding to approximately equal intervals of temperature drop.

Table 1: Height of the water recorded for every 20% increase in the water fraction

Percentage of water (%)	Height (mm)
0	0
20	10.67
40	17.69
60	24.31
80	31.33
100	42.00

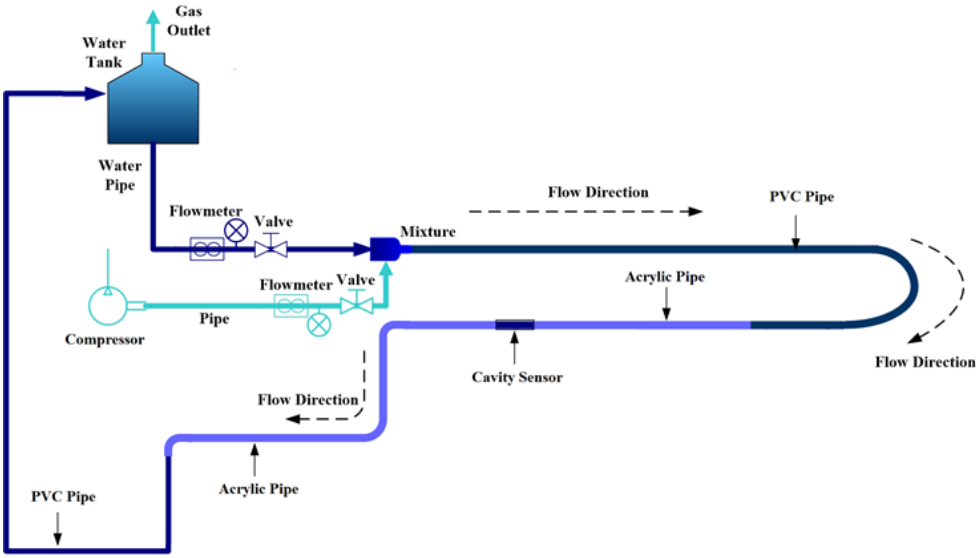

Figure 7: Schematic diagram of the two-phase flow experiment setup

4. Result and discussion

4.1. Static experiment

Figure 8 shows the microwave response curves of the gas-water fractions. Each of the curve represents a 20% change in the water fraction in the gas-water mix. The results are shown as an S_{21} measurements. The peak/resonant frequency shifts towards the right (higher frequency) as the water percentage decrease (100-0%) and the gas percentage increase (0-100%). This shift of the peak towards the right shows the decrease in the permittivity values of the mix. The amplitude also decreases as the percentage of water in the PVC pipe increase from 0-100%. The frequency shift for each of the 20% increase in the water fraction is presented in Table II. Both the shift in the frequency and change in the amplitude can be modelled together and used to distinguish between various percentages of gas-water fractions. The results also show that the maximum amplitude of each of the percentage of the water fraction dropped steadily. The resonant frequencies in this range means that the maximum amplitude can be accurately modelled using a linear equation which is a function of the change in the water fraction.

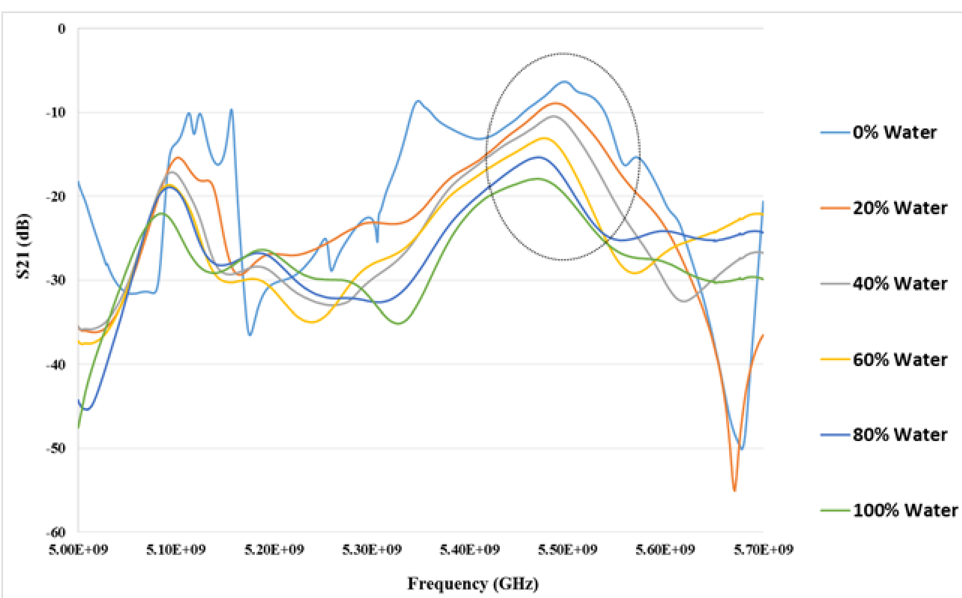

Figure 8: Graph of the S_{21} (dB), showing the change in the frequency and amplitude for different

percentages of gas-water fractions

Table 2: Frequency difference for each of the 20% increase in the water fraction

Percentage of water (%)	Resonant frequency (GHz)	Frequency difference/Shift (MHz)
0	5.496	0
20	5.487	9
40	5.485	2
60	5.473	12
80	5.470	3
100	5.469	1

4.2. Two-phase flow experiment

Figure 9 shows the response of the gas-water fraction (set to flow) to microwaves. The measurements were taken with each of the 20% change in the water fraction. The results show that there is a shift in the resonant peak of the microwave curve similar in trend to the measurements of Figure 8. It can be seen from Figure 9 that the peak of the gas-water mix with 0% water fraction is measured at the resonant frequency of 5.494 GHz. The overall shift is to the left with increase in the water fraction showing the increase in the permittivity value. The gas-water mix with 100% water can be detected at the peak frequency of 5.473 GHz. This represents an overall shift of 21.9 MHz, a significant value, considering the sensitivity of the measurement technique. The shift in the frequency with each of the change in the water fraction is shown in Table III. Similar trend to Figure 8 is observed in the amplitude where it decreased with an increase in the water percentage in the gas-water mix. The amplitude change can again be modelled as a linear equation which is a function of water fraction.

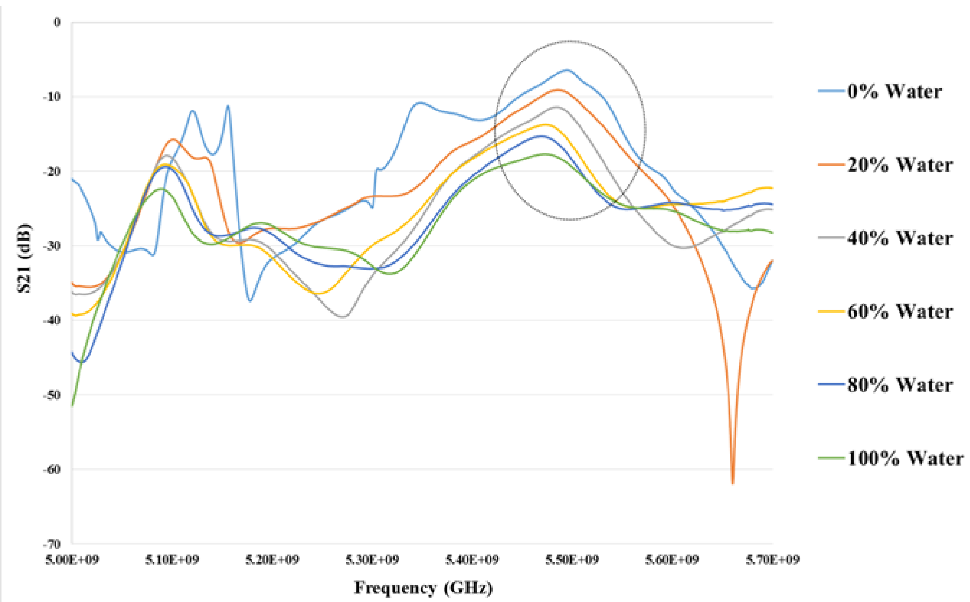

Figure 9: Graph of the S_{21} (dB), showing the change in the frequency and amplitude for different percentages of water fractions flowing through the pipe

Table 3: Frequency difference for each of the 20% increase in the water fraction in two-phase flow

Percentage of water (%)	Resonant frequency (GHz)	Frequency difference/Shift (MHz)
0	5.494	0
20	5.486	8
40	5.485	2
60	5.476	9
80	5.470	7
100	5.473	1

In Fig. 10 the changes were modeled at the maximum amplitude in the form of linear equation as the percentage volume of water increased from 0 to 100%. It can be observed that the amplitude of the microwave signal increases proportionally with the decrease in the percentage of water. The results from both the static and dynamic flow measurements of the gas-water fraction shows consistent trend. The difference in the measurements between the two is negligible.

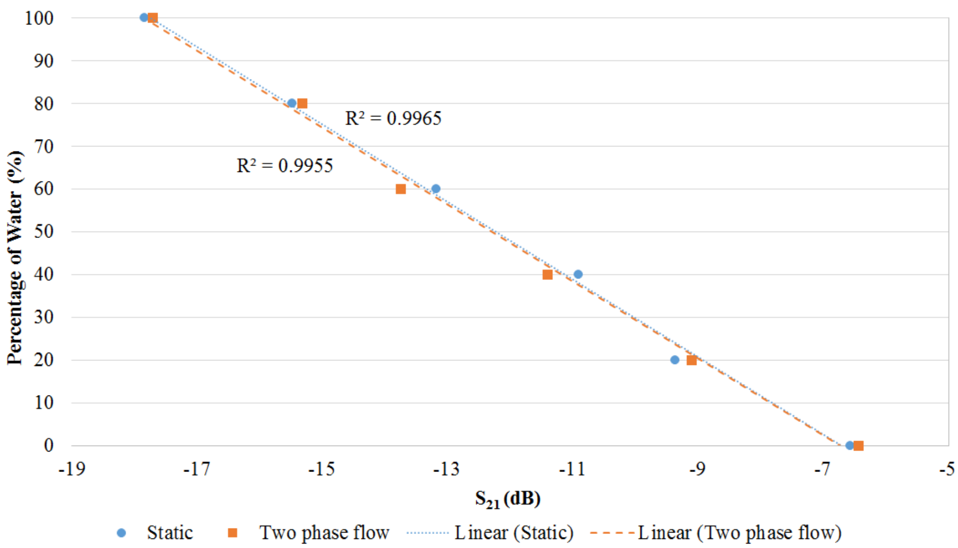

Figure 10: Statistical analysis between the static and two phase flow experimental results

4.3. Temperature independent study

Figure 11 shows the resonant peak and the amplitude of the 100% water in the pipe at different temperatures. It can be observed that the resonant frequency is almost unaffected with the change in the temperature of the water fraction. Also, the maximum amplitude did not reduce between the temperatures measured, i.e. 28-83°C. It can be concluded from Fig. 11 that the variation in temperature of water between 28-83ºC has shown not to affect the accuracy of the system, despite the change in the permittivity of the water. This is assumed to be due to the different overlapping modes such as TE_{414} and TM_{023} negating the effect, as in adjacent frequency ranges.

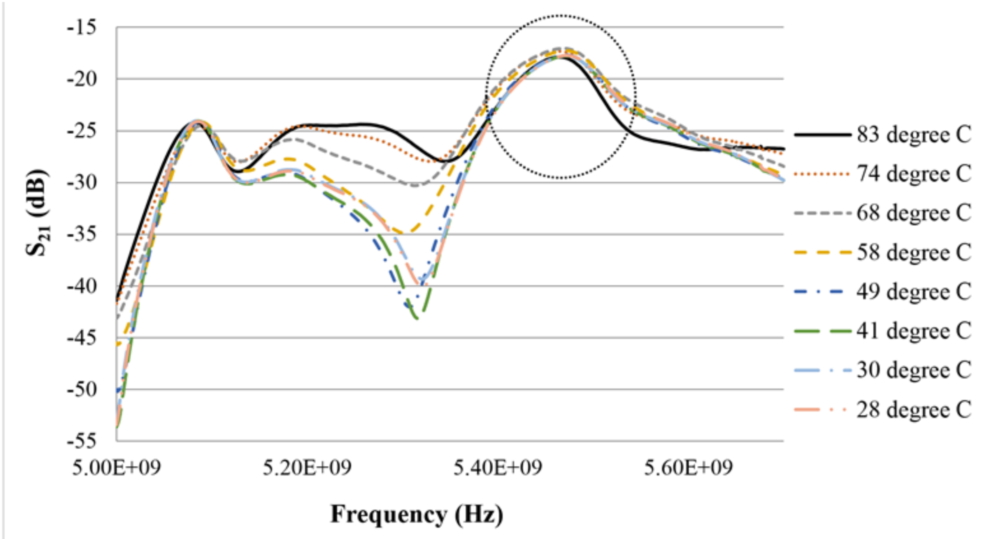

Figure 11: Graph of S_{21} measurements versus frequency for the temperature range of 28-83°C

4.4. Wavy and elongated bubbles flow measurement and detection

Figure 12 shows the snapshot of the wavy flow during the experiment. The flow rate of water was set to 8 L/min whereas the air input was set at 1.4 Nm^3/hr. The changes of amplitudes were recorded every 1.2 second and the changes of the percentage of water inside the pipe were observed. Fig. 13 shows the maximum and minimum level of water flowing inside the pipe over time. The amplitude oscillation is observed to be approximately 50-55% indicating the wavy flow.

Figure 12: Snapshot of the wavy flow produced

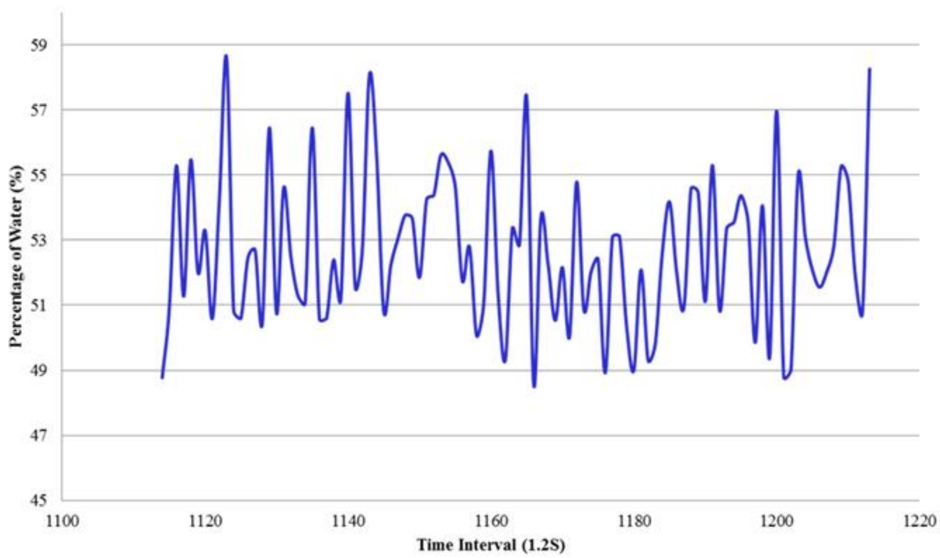

Figure 13: Graph of the percentage of water versus time for the wavy flow

Similarly, Figure 14 shows the snapshot of the elongated bubbles flow produced during the experiment.

The water flow rate was set to 18 L/min and the amount of air was fixed at 1.5 Nm^3/hr. As a result, continuous elongated bubbles flow was observed traveling along the pipe. Fig. 15 shows the maximum and minimum level of water flowing through the pipe over the period of measurements. The amplitude oscillation was significantly different in comparison to the wavy flow and was recorded approximately between 50-100% indicating the elongated bubbles flow.

Figure 14: Snapshot of the elongated bubbles flow produced

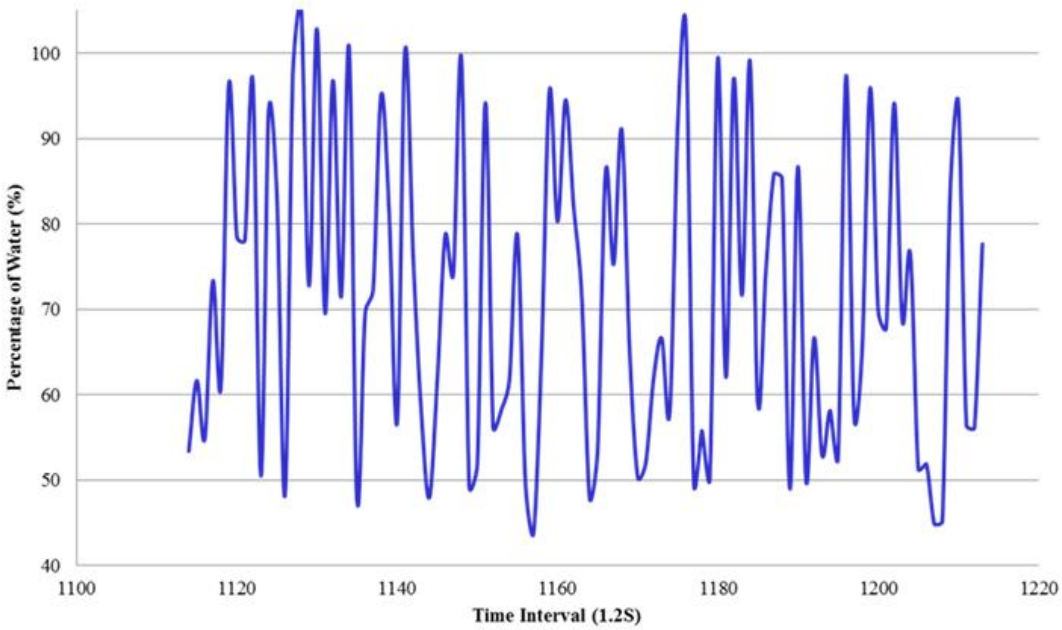

Figure 15: Graph of the percentage of water versus time for the elongated bubbles flow

4.5. Homogeneous flow measurement & detection

In order to create a homogenous flow, the test section was changed to vertical setup. Figure 16 shows the homogeneous flow regime before entering the cavity sensor. The water flow rate was set to 56 L/min and air input was varied between 0 (very low air flow rate), 1Nm^3/hr and 2 Nm^3/hr. The water and air flow meter were used in the experiment. The difference in the air input affects the amount and size of bubbles flowing inside the pipe. Tiny bubbles can be observed at low air flow rate and vice versa.

Figure 17 show the results of the microwave response to varying homogenous flow types inside the pipe with changing air input. The measurements of S_{21} parameters (transmission co-efficient) were taken between 5-5.7 GHz frequency range. It can be observed that the microwave response peaks of the minimum points (highlighted in Figure 17) shifts to the right when the air input increases. There is also a reduction in the amplitude with the increase in the air input. The curves obtained can be processed further using sophisticated analysis techniques such as neural network to determine rate of the air input. In such a case, the shift in the frequency as well as the minimum point obtained (amplitude value) can be potentially used to work out the rate of air input.

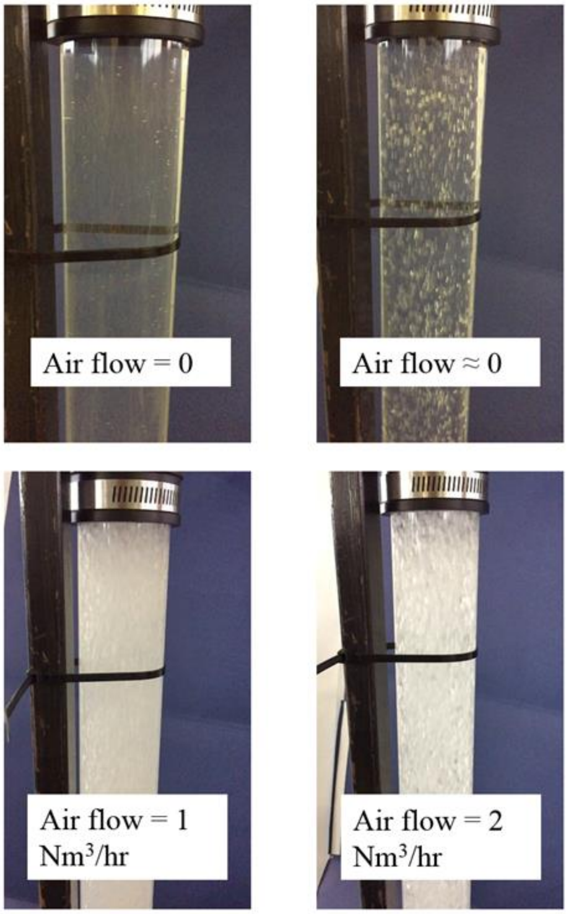

Figure 16: Snapshot of the Homogenous flow produced with different air input

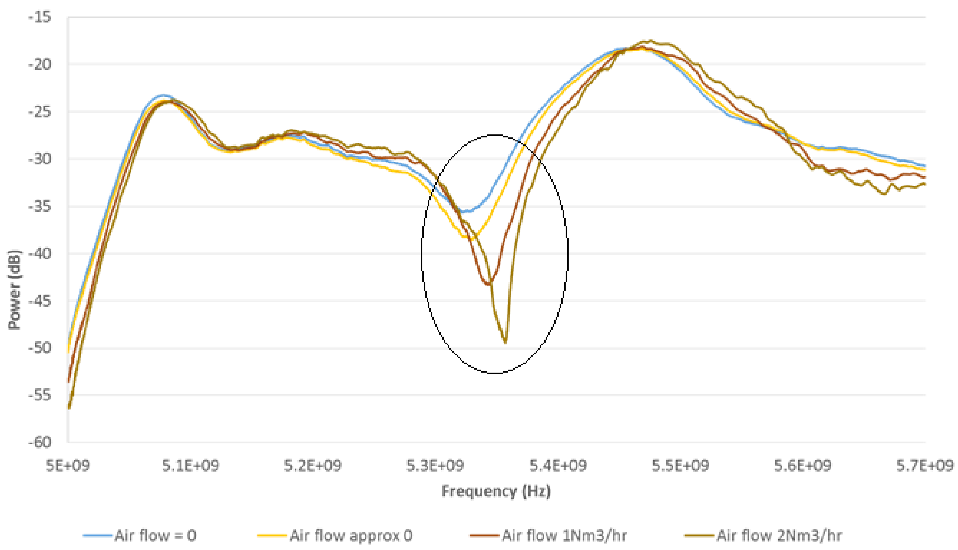

Figure 17: Graph of determination of the homogeneous flow type with varying air input using Microwave response parameter S_{21}

5. CONCLUSION

A Microwave sensor in the form of a cylindrical cavity resonator has been designed operating in the frequency range of 5-5.7 GHz. The purpose was to analyse a two phase gas-water flow regime in a pipeline. It was to identify the potential of using the microwave based sensing technique to determine various parameters in the gas-water mix such as the percentage of water and gas fractions, the types of flow regimes, temperature dependence of the technique as well as measurements and determination of the air flow rate. LabVIEW software was utilised to capture, process and display the results in real time. The results were very promising in terms of analysing the gas-water fractions. The sensor successfully demonstrated its capability to analyse various fractions of gas-water mix. The results were consistent in the case of both the static and dynamic flow. The statistical analysis of the captured data showed a linear relationship of the amplitude data with the change in the water fractions. It was also found that the technique was independent of the temperature change. The change in the temperature didn't affect the accuracy of the system despite the permittivity of the water changing. The system was also able to successfully detect the stratified, wavy, elongated bubbles and homogeneous flow regimes. Based on the results obtained it is recommended that the microwave based sensors have a potential to accurately determine various parameters in the case of flow regime measurements. The sensor and the technique can be developed further as a stable and reliable option for the industry. It is recommended that the research work should be extended to three phase measurements. Also, influence of temperature on various flow types may also be determined to evaluate the accuracy and performance of the system to operate in various industrial conditions.

6. References

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