Real Time EM Waves Monitoring System for oil Industry Three Phase Flow Measurement

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Abstract. Monitoring fluid flow in a dynamic pipeline is a significant problem in the oil industry. In order to manage oil field wells efficiently, the oil industry requires accurate online sensors to monitor the oil, gas, and water flow in the production pipelines. This paper describes a non-intrusive sensor that is based on an EM Waves cavity resonator. It determines and monitors the percentage volumes of each phase of three phase (oil, gas, and water) in the pipeline, using the resonant frequencies shifts that occur within an electromagnetic cavity resonator. A laboratory prototype version of the sensor system was constructed, and the experimental results were compared to the simulation results which were obtained by the use of High Frequency Structure Simulation (HFSS) software package.

1. Introduction

The output of an oil and gas reservoir consists of an oil, gas, and water mixture. Gas and water are produced, as a natural phenomenon, which occurs in the petroleum field, when oil is extracted from a well. In addition to that, water and gas might be injected at various points into the well to maximize the amount of oil that can be retrieved. The injected water is used to maintain the pressure within the well as the oil is removed, and gas may be used to reduce the viscosity of the oil. Measuring and monitoring the produced mixture fractions (oil, gas, and water) are very important requirements, in order to enhance the quality aspects of production, and optimize the process for both operation and transportation.

Multiphase metering provides valuable information for the management of oil and gas field, as it enables the quantities of oil, water, and gas to be determined and monitored as they flow through the measured pipeline. Particularly, it enables decisions to be made that can maximize the hydrocarbons that are extracted from each well in the most efficient manner. Accurately measuring the amount of oil, gas and water flowing in a single conduit is challenging and a wide range of techniques have been adopted in the search for a reliable meter [1-4]. The two common methods, which are used for measuring oil, gas, and water fractions in a multiphase flow, are based on ß-ray attenuation and electrical impedance techniques. In addition to these methods, there are a number of alternative techniques for measuring component fractions that have been developed for industrial applications. These techniques include microwave attenuation and phase shift, impedance based methods, pulsed neutron activation and nuclear magnetic resonance [5-9].

The sensor discussed in this paper is based upon a cylindrical cavity and it uses the relationship between the resonant frequencies that occur and the permittivity of the fluid flowing through it. The resonant frequency for a \( \text{TE}_{mnl} \) mode in a cylindrical cavity [10] can be calculated using equation (1).
\[ f_{nm} = \frac{c}{2\pi \sqrt{\mu_r \varepsilon_r}} \left[ \left( \frac{p_{nm}}{b} \right)^2 + \left( \frac{l}{d} \right)^2 \right]^{1/2} \]  

where \( c \) is the velocity of light  
\( \mu_r \) is of the relative permeability  
\( \varepsilon_r \) is the relative permittivity  
\( p_{nm} \) is the m\textsuperscript{th} root of the first derivative of Bessel function of the n\textsuperscript{th} order  
\( b \) is the radius of the cavity  
\( d \) is the depth

2. Sensor Design and HFSS Simulations

The sensor discussed in this paper is based upon a cylindrical EM cavity, which resonates at particular frequencies that depend upon the dimensions of the cavity and the permittivity of the fluid flowing through the cavity. Due to the polarity, the water permittivity (\( \varepsilon_r = 81 \)) is higher than that of either the oil (\( \varepsilon_r = 2-2.5 \)) or the gas (\( \varepsilon_r = 1 \)), so any small change in the water fraction produces a large frequency shift.

Electromagnetic (EM) waves cavity resonance occurs when the electric and magnetic fields form a standing wave, so different EM wave modes can occur in any particular cavity, each with its own resonant frequency [11, 12]. The fundamental modes for cylindrical cavities are the TE\textsubscript{111} and TM\textsubscript{010} modes. TE Modes (Transverse Electric) have a magnetic component in the propagation direction (and TM Modes (Transverse Magnetic) have an electric component in the propagation direction. Each mode will generate a resonant peak with a quality factor (\( Q \)), which is inversely proportional to the power dissipated in the cavity for each applied EM wave oscillation. A high \( Q \) indicates a sharp resonant peak that will be more readily analyzed and improve the accuracy of the sensor.

To design a sensor that can monitor the fluid mixture flow in a pipeline without obstruction and erosion, the sensor has to be fitted to a pipeline, so the cavity must be open at both ends. By making the cavity diameter larger than the pipeline diameter, and by using a dielectric liner, the pipeline can be made to appear continuous [13] as shown in Figure 1. Using this technique allows the resonant frequencies to be affected by the contents of the pipeline, and separates the antennae, which are used to excite the resonant modes, from the fluid in the pipeline. This both protects the antennae from the moving fluid and enables the pipeline to be cleaned with the sensor in place.

The permittivity of the outer cavity is therefore independent of the fluid inside the pipeline, aside from possible temperature dependence. Further the simple relationship between the permittivity and the resonant frequency is described by equation (1). Further more, the introduction of the open ends cavity and the high dielectric materials in the sensor (pipeline and outer cavity) required a powerful modeling and simulation software package to solve the complex Maxwell's equations. This research considers using water in the outer cavity and Oil/Water/Gas in the inner cavity (pipeline) [14, 15].

![Figure 1: Pipeline Cavity Sensor](image-url)
The designed sensor was simulated, and the simulated results were obtained. Figures 2 and 3 show the simulated results, using a cavity with an outer radius = 50 mm and depth = 300 mm, and a PVC pipeline with an outer radius = 25 mm. The results show the E-Field Vectors the fundamental mode with minimal distortion. On the other hand, it was possible to determine that the cavity ends would only result in a slight loss in Q and would therefore not hinder the concept from working.

Figure 2: The simulated E-field for 0% water and 100% gas

Figure 3: The simulated E-field for 100% water and 0% gas

Figure 4: The simulated resonant frequencies shifts for 0 to 100% water/gas

The HFSS simulation resonant frequencies for this mode are shown in figure 4. As the water and gas percentages volume in the pipeline (inner cavity), increased from 0-100%, the frequency shift is 35 MHz.

3. Prototype, and Experimental and Real Time Results

The sensor prototype set up is shown in Figures 5, 6 and 7. This prototype uses the Marconi 6200 Instrument (MTS 10MHz -20GHz), and it consists of the Microwave Cavity System, Online Data Logging (disc top computer), simulation computer (laptop computer), temperature control unit, temperature sensors, and Feed Pump. In addition to the loop antenna (transmitting and receiving antenna), and a PVC pipe. The PVC pipe was used to represent the oil pipeline. The depth of the cavity was chosen so that the TE111 mode would occur at a lower frequency to avoid the multi-resonates of the water in high frequencies, and to make it easy to be identified on the spectrum analyzer. The cavity was sealed to not allow leakage of liquids (water/Oil).

The prototype was initially tested by raising the water volume percentages in the horizontal pipeline from 0-100%. On the one hand, the same procedures were applied to the Oil volume percentages which were varied from 0-100% in the pipeline. On the other hand, the system was tested by varying the mixture (Oil, Water, and Gas) volume percentages in the pipeline from 0-100%. Figures 8 and 9 show the TE111 mode spectrums which captured during testing of the prototype sensor, when the percentages volume of water/gas/oil mixtures increased from 0-100% in the pipeline, in steps
of 10%. As the volume percentages of the mixtures (water/gas/oil/gas) increased from 0%-100% in the pipeline, the frequency shift increased as well.

Figure 8 shows how the fundamental mode peak changes as the percentage volume of water/gas mix in the pipeline increased from 0-100%. The total frequency shift for this mode between 0% water to 100% water in the pipeline is 32 MHz, which corresponds closely with the frequencies predicted by HFSS. Figure 9, shows the changes in frequency as the percentage volume of oil/gas mix increased from 0-100%. The frequency shift is about 4 MHz. Further, an in depth study and analysis of TE modes and others modes are published in [15]. From Figures 8 and 9, with respect to increasing the volume of liquid percentages in the pipeline, it can be clearly seen that the applied microwave signal amplitude increases proportionally and the frequency decreases universally respectively. Further more, the frequency and amplitude and reflection coefficient of the applied signal, permittivity of liquid, and the effect of temperature were investigated and analyzed.
A not-intrusive sensor was designed based on a cylindrical cavity resonator to detect changes in permittivity within a pipeline for multiphase metering (oil, gas, and water), by monitoring the resonant frequency shifts of the fundamental mode. The sensor was designed to be non intrusive and simulated, using HFSS, and a laboratory prototype was constructed. The experimental and simulated results were obtained, analyzed and compared. This research was advanced and software application was designed to enable the system to display the results online. The system was connected and tested online using NI software and hardware. The real time results of the system proofed the ability of the system to determine any small change in volume percentages of the mixture of (water/oil /gas). Finally, the system was automated, using National Instrumentation (NI) devices and Lab view software package, and an online real time results are read and captured.

Conclusion

Finally, a software application was designed to enable the system to display a real time results, and a database was built using the experiential results. Figure 10 shows the system front panel while Figures 11, 12, 13 and 14 show online screen shots for 0%-100% oil/water/gas.

Figure 8: Experimental results: Resonant frequencies shifts for 0 to 100% water/gas

Figure 9: Experimental Results: Resonant frequencies shifts for 0 to 100% oil/gas

Figure 10: Experimental results: Resonant frequencies shifts in TE111 for 0 to 100% water/gas

Figure 11: Resonant frequencies shifts in TE111 for 100% water

Figure 12: Resonant frequencies shifts in TE111 for 100% Oil
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