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A microwave cavity resonator sensor for water-in-oil measurements

Prafull Sharma*, Liyun Lao, Gioia Falcone

Oil and Gas Engineering Centre, Cranfield University, United Kingdom

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ABSTRACT

Online monitoring of Water-Liquid Ratio (WLR) in multiphase flow is key in petroleum production, processing and transportation. The usual practice in the field is to manually collect offline samples for laboratory analysis, which delays data availability and prevents real time intervention and optimization. A highly accurate and robust sensing method is needed for online measurements in the lower end of WLR range (0%–5%), especially for fiscal metering and custody transfer of crude oil, as well as to ensure adequate flow assurance prevention and remedial solutions. This requires a highly sensitive sensing principle along with a highly precise measurement instrument, packaged together in a sufficiently robust manner for use in the field. In this paper, a new sensing principle is proposed, based on the open-ended microwave cavity resonator and near wall surface perturbation, for non-intrusive measurement of WLR. In the proposed concept, the electromagnetic fringe field of a cylindrical cavity resonator is used to probe the liquid near the pipe wall. Two of the cylindrical cavity resonance modes, TM010 and TM011 are energized for measurements and the shift in the resonance frequency is used to estimate liquid permittivity and the WLR. Electromagnetic simulations in the microwave frequency range of 4 GHz to 7 GHz are used for proof-of-concept and sensitivity studies. A sensor prototype is fabricated and its functionality demonstrated with flowing oil-water mixtures in the WLR range of 0–5%. The frequency range of the proposed sensors is 4.4–4.6 GHz and 6.1–6.6 GHz for modes TM010 and TM011, respectively. The TM011 mode shows much higher sensitivity (41.6 MHz/WLR) than the TM010 mode (3.8 MHz/WLR). The proposed sensor consists of a 20 mm high cylinder, with a diameter of 30 mm and Poly-Ether-Ether-Ketone (PEEK) filler. The non-intrusiveness of the sensor, along with the high sensitivity in the resonance shift, makes it attractive for practical applications.

1. Introduction

Monitoring of the WLR in multiphase flows is essential in petroleum production, processing and transportation. Traditionally, offline samples are taken in the field and used to measure the WLR in fluid analysis laboratories, making the data availability a lengthy process, with lack of real-time information. This, in turn, delays operational decision in the field, which may lead to unoptimized processes and lost production. A precise online measurement of WLR is highly desirable, but has proven to be challenging in the lower end of WLR range, particularly when high accuracy is required [1]. Online WLR meters (sometimes referred to as water cut meters) are commonly based on sensing one or combination of the dielectric permittivity, density, infrared or gamma-ray spectral absorption characteristics of the oil and water mixture [1].

Among these methods, WLR sensing using the contrast in the permittivity of oil and water has already been the subject of extensive academic as well as industrial research. One of the earliest proposals was made by Dykesteen et al. [2] consisting of a method of non-intrusive measurement of fluid fractions using two insulated electrodes and flowing multiphase mixture between them. The electrical impedance is measured and used to estimate the fractions of water, oil and gas. Methods based on electrical capacitance have also been developed, though measurement uncertainty and instrument drift issues limits their usage for high accuracy requirements. Hammer et al. [3] demonstrated a helically shaped capacitance electrode system for water fraction in oil-water mixtures with repeatability better than 1.5% [3]. They also demonstrated that helically shaped electrodes are less dependent on variation in flow regimes. Sami et al. [4] investigated a variety of capacitance designs to determine volume fractions in two-phase pipelines and concluded that a double helix electrode provides the most practical and linear sensor response in various flow regimes. Demori et al. [5] proposed a solution to the problem of capacitive sensing in the presence of conductive water, which introduces parasitic coupling to stray elements outside the measurement section of the pipe. They proposed a novel sensor configuration that

* Corresponding author.

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Nomenclature

WLR	Water-liquid ratio
ε	Dielectric permittivity
μ	Magnetic permeability
E_1	Electric field in unperturbed cavity
H_1	Magnetic field in unperturbed cavity
ω	Resonance frequency (radians/s)
V	Volume
TM	Transverse electric mode
TE	Transverse magnetic mode
f	Resonance frequency (Hz)
J_m	Bessel function of mth order
P_{mn}	Root of J_m (n^{th} root)
α_w	Fraction of water

employs guard electrodes, coupled to a tailored electronic interface to drive the guard electrodes. Chen et al. [6] investigated a coaxial capacitance sensor which they validated in a vertical upward oil-water two-phase flow experiment, and effectively applied time-frequency analysis to estimate water fraction in low water-cuts.

Electrical tomography based methods have been gaining interest especially for multiphase flow imaging and phase fraction estimation, although industrial versions for field use are still being developed. Yang [7] extensively reviewed the electrical capacitance tomography technology and provided design guidance. The measurement problem is particularly complex at the lower end of the WLR range (0–5%), where poor contrast in dielectric permittivity (ε_r) between the oil-water mixture and the oil alone proves to be a challenge for applications demanding high accuracy [8].

Thanks to the increasing availability of precise electronics, driven by rapid developments in the telecom industry, microwave-based sensing solutions for robust and accurate WLR measurement have been emerging rapidly. Castle et al. [9] developed one of the earliest microwave-based sensing systems for water fraction measurement in crude oil applications. Microwave-based sensing principles can be broadly categorized into methods based on wave transmission, reflection and resonance. Various microwave sensing methods for industrial applications have been systematically reviewed by Nyfors [10].

Microwave resonance based principles are attractive for field use due to high precision and robustness against instrument drift [10]. Microwave based intrusive resonance sensor have been successfully demonstrated with real oil field applications and offered commercially [11]. They have also been used to estimate conductivity and salinity of water present in the multiphase mixtures [12]. Nyfors [13] developed an intrusive resonator method for detecting phase fraction in multiphase flows, particularly suited for wet gas applications. It consisted of a fin resonator as an intrusive feature of the pipe to create a resonator within the pipe structure. Subsequently, several other sensing principles were developed with non-intrusive microwave resonators. Wylie et al. [14] demonstrated a cavity resonator sensor principle which is non-intrusive and transmits low power (10 mW) radio frequency in the range of 100–350 MHz. They further developed an industrial version of the sensor and tested it in an industrial flow setting. Karimi et al. [15,19] developed a planar microwave sensor with a T-resonator design for non-intrusive WLR sensing over the full range of operation (0%–100% WLR). The proposed method uses screen printing with a 3D printed mask directly onto the pipe surface. The resonance frequency of the T-resonator changes in the frequency band of 90 MHz–190 MHz (111%) with changing water fraction in oil from 0% to 100%.

Surface perturbation methods have gained research attention due the near wall measurement they provide that can be effective in measuring liquid properties even in the presence of gas. Furthermore, resonance based microwave sensors are evaluated for demanding applications, such as waste water with very low concentration of oil [16]. Ni and Ni [17] described a class of non-intrusive microwave resonator sensors, called extra-cavity perturbation methods, for generic applications. A sensing principle based on surface perturbation of a microwave dielectric resonator was developed by Nyfors [18] for application to wet gas flow with non-intrusiveness as a key advantage.

Zarifi et al. [20] established a microwave planar ring resonator sensor tuned at 5.25 GHz, providing a non-contact method for liquid–liquid interface detection. They demonstrated the applicability of this sensor to interface detection in water-olive oil-ethanol samples representing a wide range of permittivity. The resonator's Quality Factor (Q-Factor) is also used in the estimation process, in addition to the resonance frequency, to increase the robustness of the sensor.

Microwave resonators have been investigated for demulsification of water in crude oil using single- and multi-mode resonators [21].

Oon et al. [22] investigated a cylindrical microwave resonator sensor to monitor two phase flow systems and the changes in the permittivity of the measured phases to differentiate between the volume fractions of air, water and oil. Microwaves in the range of 5–5.7 GHz have been used to analyse a two-phase air-water and oil-water stratified flow in a pipeline, demonstrating the ability to detect a change in water fraction in full range of 0%-100%.

Zarifi and Daneshmand [23] proposed a non-contact liquid sensor using an active, feedback loop assisted, planar, micro-strip microwave resonator. The sensor has the ability to operate in a non-contact fashion within a distance of 0–8 cm. The active loop technique is shown to increase the primary Q-Factor from 210 to 500,000 in air when measured at a resonant frequency of 1.52 GHz. The proposed device is used to distinguish between water, ethanol, methanol, isopropanol, and acetone in a submerged tube inside a water-filled container. They also demonstrated the application of micro-strip microwave resonator sensor in monitoring solid particle deposition in lossy medium [24].

Al-Kizwini et al. [25] proposed a non-intrusive sensor, which is based on an electromagnetic waves cavity resonator. It determines and monitors the percentage volumes of each of the two phases (oil and gas) in the pipeline using the resonant frequencies shifts that occur within the resonator. Temperature has a significant influence on the liquid permittivity, especially for water. It also affects the resonance frequency of the measurement by microwave resonators and hence it is important to compensate the measurements against variations due to temperature [26].

From the literature review, it can be observed that microwave resonator based sensing principles have been gaining more and more attention with varied multiphase flow measurement applications. In this paper, in order to address the need for online, near-wall WLR sensing, a novel, non-intrusive surface perturbation microwave cavity resonator is proposed in the frequency range of 4.4–4.6 GHz and 6.1–6.6 GHz, with active modes TM010 and TM011, respectively. Measurement of low WLR in two-phase (oil-water) flow and the proof-of-concept is established by means of simulations and experiments at constant temperature.

2. Sensing principle

A schematic of the proposed cylindrical cavity resonator sensor in contact with the flowing liquid is shown in Fig. 1. The flat open surface of the sensor interacts with the liquid to measure its per-