

Sergey Y. Yurish, Editor



Advances in Measurements and Instrumentation: Reviews

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Book Series, Volume 1

S. Y. Yurish
Editor

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S. Y. Yurish, *Editor*

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Chapter 4

Recent Advances in Water Cut Sensing Technology

Prafull Sharma and Hoi Yeung

4.1. Introduction

Multiphase Flow Meters (MPFM) are increasingly being used for both subsea and offshore applications. They are gaining acceptance due to the benefits they bring over test separators, production control and flow assurance to name a few. Multiphase Flow Meters commonly use the measurement of mixture density or electrical permittivity of the produced mixture for estimation of phase fractions [1]. Water cut meter is often part of multiphase flow meters for measurement of water content in the multiphase mixtures. There are standalone water cut meters utilized in the oil and gas production. In this chapter, water cut measurement technologies and methods are discussed and their gaps identified. Microwave based water cut measurement is then described in greater detail along with key academic and industrial research trends.

4.2. Water Cut Measurement Technology

Water cut measurement is an essential component of most multiphase meters and normally is also a part of their final output. By monitoring water cut, operators can optimize the oil production rate, chemicals injection rate, detect water breakthrough among other production and flow assurance operations. Standalone water cut meters are also used in several segments of the oil and gas industry and there are several

measurement methods available (Fig. 4.1). Other generic application segments of water cut meters are:

- Upstream: Production well-head, gas-liquid separator, liquid-liquid separator, fiscal and allocation metering, Custody transfer;
- Midstream: Fiscal measurements, condensate water, fiscal metering;
- Downstream: Refinery crude feed, de-salter feed and control, fiscal quantity and quality measurement, shipping terminals, refined products, crude loading and unloading.

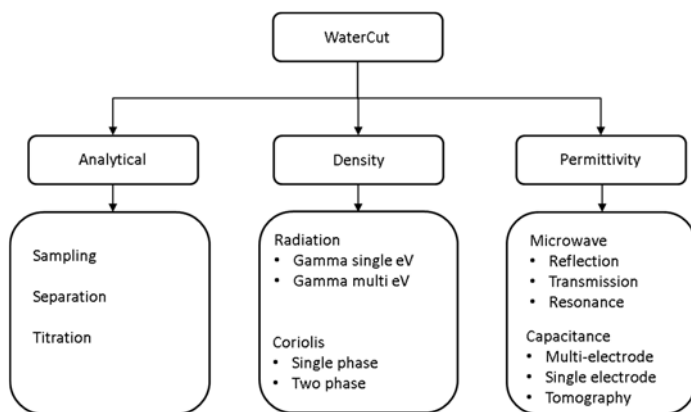


Fig. 4.1. Common principles for water cut measurements.

4.2.1. Analytical Methods

4.2.1.1. Sampling and Centrifugal Separation

In this traditional method, a sample of the oil-water mixture is taken from the production stream through a sampling probe or a sampling port on the pipeline. Then, the oil and water are separated using a centrifuge. Finally, the volume of the separated water is measured, and the water cut of the sample is calculated based on the total volume of the liquid sample.

This method is often used in laboratory tests. It is also widely used to calibrate other water-cut meters. However, the following disadvantages limit its field applications. Firstly, it cannot provide a continuous

measurement. In addition, this method is time-consuming, the accuracy is questionable, and personnel are exposed to hazardous chemicals. Note that the sampling, separation and measurement process of live hydrocarbons requires adherence to strict Health, Safety and Environmental (HSE) rules. Most importantly, the water cut measurement accuracy strongly depends upon the integrity of the fluid sample. The sample is affected by many factors such as the phase distribution inside the pipe, location and orientation of the sampling probe and/or sampling port, and the skill of the sampling personnel.

4.2.2. Density Measurement Methods

4.2.2.1. Differential Pressure Method

When an oil-water mixture flows through a vertical pipe with a constant internal diameter, the total pressure drop is composed of two terms: gravitational pressure drop (or hydrostatic pressure drop) and frictional pressure drop. The latter term is often negligible if the mixture velocity is not extremely high. If the total pressure drop through a section of vertical pipe is measured with a differential pressure transducer, the hydrostatic pressure drop of the oil-water mixture can be obtained by ignoring or estimating the frictional pressure drop. The hydrostatic pressure drop of the oil-water mixture through the vertical pipe can be expressed as follows in equation (4.1),

$$\Delta P_g = gL[\rho_w WC + \rho_o(1 - WC)], \quad (4.1)$$

where g is the gravitational acceleration, L is the length of the vertical pipe section, WC is the water-cut, and ρ_o and ρ_w are the densities of oil and water, respectively. Clearly, the water-cut can be calculated from equation 4.1 when the oil and water densities are known.

This is a very simple and low-cost method, only requiring a commercially available differential pressure transducer [2]. It gives continuous, real-time measurement with negligible pressure loss. The accuracy of this method is strongly dependent on the difference of oil and water densities. For light oil systems, it gives acceptable measurement accuracy due to the significant density difference between the oil and water phases. The water cut measurement accuracy decreases with a decrease in the difference of oil-water densities. Another disadvantage of this method is that entrained gases will have a

detrimental effect on the measurement since a small amount of entrained gases can cause a significant change in the differential pressure across the vertical pipe. An additional problem is in obtaining a good oil density at operating pressure and temperature. Laboratories often report dead oil density at room temperature with no solution gas. This density can be very different from that of flowing live crude oil.

4.2.2.2. Gamma Ray Densitometer

Density-based water cut meters often utilize gamma-ray densitometry which is a nuclear source. However, the adoption of gamma-ray densitometers has been limited for offshore and topside applications due to concerns over the use of a radiation source. The logistics and regulatory procedures around the handling of gamma source make it inconvenient for the end users. Gamma-ray densitometer is a well-adopted sub-component for subsea MPFM and is among the most reliable measurements. Both single energy and dual energy gamma-ray technology are used in the measurement of density and to compensate for additional effects as salinity. Beams of gamma rays are attenuated by the materials through which they pass. The absorption of a beam of initial intensity I_i (photons per square meter per second) is described by an exponential absorption law as follows in equation (4.2)

$$I = I_i \exp[-\beta z], \quad (4.2)$$

where β is the mass absorption coefficient and z is the distance travelled through a homogeneous absorbing medium.

When applying this technique to an oil-water emulsion flowing inside a pipe, a collimated beam of gamma rays is passed through the pipe wall, through the oil-water-gas three-phase mixture, and through the opposite pipe wall before it reaches the detector. The water-cut of the oil-water-gas emulsion can be determined by the following equation (4.3)

$$I = I_i \exp\{-(\beta_o \rho_o f_o + \beta_w \rho_w f_w + \beta_g \rho_g f_g) d\}, \quad (4.3)$$

where β , ρ and f are respectively the mass absorption coefficient of the gamma-rays, the density and the volume fraction of the mixture component in the gamma-ray path; subscripts o, w and g respectively refer to oil, water and gas; d is the internal diameter of the pipe, and Dual-energy gamma ray absorption technique has been used to measure the water-cut in oil-gas-water three-phase flow. The attenuation of the

gamma rays by the fluid is measured at two different energy levels. By performing measurements at two different gamma-ray energies, two equations can be used with different values of mass absorption coefficients. The volume fraction of oil, water and gas can be calculated from these two equations using mass absorption coefficients for the particular gamma-ray energy and knowledge of the densities and composition of the oil, water and gas.

4.2.2.3. Coriolis Densitometer

Coriolis metering technology for water cut and multiphase flow is actively worked upon by several research groups and is continuing to develop rapidly [3]. Coriolis measurement principle is one of the most accurate metering techniques for single phase applications. Since Coriolis meters also measure the density of the fluid passing through it, they can be used in the measurement of water cut in case of oil-water mixtures. A typical Coriolis force flowmeter has two identical tubes that are vibrated in opposition at their natural frequency by an electromagnetic drive mechanism. Because of the Coriolis effect, the fluid flowing through the vibrating tubes creates an asymmetric distortion between the inlet and outlet legs. The distortion magnitude, measured by two position detectors placed on opposite tube legs, is directly proportional to the mass flow rate. Besides mass flow rate, the fluid density can also be determined from the change in vibrating frequency of the meter tubes. A resistance-type temperature sensor continuously monitors the meter tube temperature for various signal processing purposes. Since the Coriolis meter has no moving parts within the flow path, it requires significantly less maintenance.

Water-cut (WC) is calculated from the measured emulsion density (ρ_m) using the definition of mixture density as per the equation (4.4):

$$\rho_m = \rho_w WC + \rho_o(1 - WC), \quad (4.4)$$

where ρ_o and ρ_w are the densities of oil and produced water, respectively.

Because water-cut is based on density difference between oil and water, measurements can be obtained over the full range of 0-100 % water cut if accurate flowing density is available for the oil and water. This is true regardless of whether the emulsion is oil-continuous or water-continuous.

Although Coriolis flow meters are highly accurate for single phase metering, their performance in oil-water mixtures is not quite trustworthy as shown by several research studies [3]. Moreover, even a small fraction of gas can adversely affect the measurement results.

Since density based water cut measurement is dependent on density contrast between oil and water, they are not a preferred method for heavy oil metering where the density of oil and water are much closer to each other.

4.2.3. Infrared Method

This is a technology based on the bulk transmission of infrared radiation through an oil-water mixture [4]. Its basic principle is spectroscopy which relies on the large difference in absorption of infrared radiation by crude oil and water. Over a very narrow band of radiation, the wavelengths for water are effectively transparent and oil is a strong absorber. The Infrared water-cut meter is a full-range water, and it is unaffected by the transition from oil-continuous phase to water-continuous phase.

4.2.4. Permittivity Measurement Methods

Permittivity based methods (Fig. 4.1) utilize the fact that the permittivity of oil ($\epsilon_r \sim 2-3$) is much lower than that of water ($\epsilon_r \sim 50-80$). A good review of methods for industrial measurements is provided by [5]. The contrast in permittivity of oil and water is a result of their respective non-polar and polar molecular structures. Since, this contrast in permittivity is maintained irrespective of the type of oil – light or heavy, permittivity based measurements are attractive for a wide range of applications. Moreover, unlike gamma densitometers, Permittivity measurement meters do not use ionizing radiation. This is another factor which makes them attractive for end users especially for topside and offshore applications.

There are primarily two techniques used for permittivity based water cut measurements. RF / Microwave based sensors (100 MHz – 10 GHz) have emerged rapidly for water cut measurements. Yet another popular measurement principle is to utilize capacitance measurements between electrodes to measure fluid permittivity at frequencies below 10 MHz.

4.2.4.1. Capacitance, Conductance & Impedance Principles

Impedance is an important parameter used to characterize electronic circuits, components, and the materials used to make them. The measurement of capacitance can be accomplished by measuring impedance [6]. A typical capacitance probe uses a cell composed of two plates or an open circuited centre rod with a circular pipe as the outside element. Fluid flows through the space separating the inner and outer electrodes [7-10].

The parallel plate capacitance method measures the electrical energy storage based on the dielectric constant of the material between the two plates. The dimensions are fixed and the capacitance value varies only with a change in the insulator fluid (oil) composition which affects the dielectric constant. This can be predicted in terms of the dielectric constant which gives rise to the impedance of the capacitor so formed. A dielectric constant is a dimensionless number; it simply expresses the ability of a material to be polarized and therefore stores electrical energy. Since the measured capacitance (impedance) is proportional to change in dielectric constant (due to water-cut), using the relationship of the dielectric constant to the capacitance, the measured capacitance can be converted to a water content output signal. Analysers based on capacitance measure principles are accurate only when water-cut is relatively low and the oil/water emulsion is oil-continuous (i.e., water droplets in oil-continuous phase). Because these analysers depend on dielectric properties of the emulsion, erroneous measurements occur at higher water cuts even before the emulsion becomes water-continuous (i.e., oil droplets in the water-continuous phase). The relationship is non-linear above approximately 10 % water percentages. In most cases, the highest water-cut of the oil-continuous emulsion occurs at about 35-60 %. If the medium under measurement does not absorb much of the low-frequency energy, capacitance measurements are accurate in the range of water cuts between 0.5 % to 15 %. When the crude oil absorbs energy it is no longer a pure capacitance measurement but, it also has a conductive portion which creates an error in the capacitance measurement. Some crude oils do absorb energy and therefore the measurement becomes more difficult since this further reduces the sensitivity as this becomes a two variable measurement instead of just one variable system. Capacitance measurement is a single factor measurement, it only measures the amount of energy stored between two metal plates, and this limits the capability of this type of measurement.

Imaging techniques have been developed by several researchers using electrical impedance methods. Wiremesh sensors are used in laboratories to study the spatial distribution of phase fractions [11]. Tomographic measurement systems using Electrical Resistance Tomography (ERT), Electrical Capacitance Tomography (ECT) or Electrical Impedance Tomography are getting more matured for field use however they still are largely laboratory measurement techniques [12]. Kvandal *et al.* (2010) and Schuller (2004) [13, 14] described a SECAP sensor which is a non-intrusive single-ended configuration of capacitive water cut measurement. Zhai (2015) [15] described a liquid holdup measurement with double helix capacitance sensor for horizontal oil-water flow.

4.2.4.2. Microwave Principles

Microwaves and Radio Frequency (RF) waves are electromagnetic waves which can travel in dielectric media. Conventionally, the frequency range of 3 MHz – 300 MHz is classified as radio frequency (RF) whereas the spectral range of 300 MHz – 300 GHz is considered to be microwave frequency range. However, in practice, the sensors operating either in RF or microwave are generalized as microwave sensors. Katze and Hubner (2010) [16] reviewed the electromagnetic techniques to water content determination of materials.

Industrial microwave sensors have been in existence for several decades but their development and industrial adoption have accelerated in recent years, mainly due to miniaturization and availability of cheaper components. Many of the new measurement problems which have been tackled by different kinds of microwave sensors are described by Nyfors (2000) [17].

Microwave based water cut sensors fall into the category of material property measurements, where the permittivity of an oil-water mixture is measured to estimate the water content. The complex permittivity and permeability of the medium in which electromagnetic waves propagate affect the wavelength, speed and attenuation of the wave. Gregory and Clarke (2006) [18] described RF and Microwave techniques for dielectric measurements on polar liquids. By measuring the permittivity of a mixture, and using the permittivity of mixture constituents, the phase fraction of constituents can be estimated using an appropriate mixture model.

Microwave sensors are attractive because they are not limited by the health risks associated with radioactive radiation based meters and their fairly low accuracy or the undesirable influence of contamination on the capacitive sensors.

A summary of the water cut measurement methods is show in Table 4.1.

Table 4.1. Summary of the methods for water cut measurement.

Method	Category	Key advantages	Main limitations
Sampling	Analytical	Traditional and robust	Manual, offline and time consuming
Differential Pressure	Density	Differential Pressure measurement is a robust measurement and has large knowledgebase	Accuracy dependent on flow regimes, mixture transition zone and sensitive to gas presence
Gamma Ray Absorption	Density	Robust measurement, Clamp-On configuration	Nuclear radiation concerns users, oil-water density contrast can be low specially for heavy oil
Coriolis Meter	Density	High accuracy and high precision, mature technology for homogenous fluid flow	Sensitive to mixture homogeneity, sensitive to gas presence
Infrared	Permittivity	Spectrometric technique can measure multiple component fractions	Small iris and slot size limits use in heavy oil in poor mixtures
Impedance, Capacitance, Conductance	Permittivity	High dielectric contrast between oil and water	Method range dependent on mixture type such as oil-in-water (o/w) or water-in-oil (w/o)
Microwave	Permittivity	High dielectric contrast between oil and water. Non-ionization radiation is better for health and safety considerations.	Dependency of water cut estimation on mixture models which may be dependent on flow regimes and mixture types

4.3. Microwave Measurement Technology

4.3.1. Industrial Microwave Sensing Principles

The most common water cut measurement types can broadly be categorized based on microwave transmission, reflection and resonance as shown in Fig. 4.2.

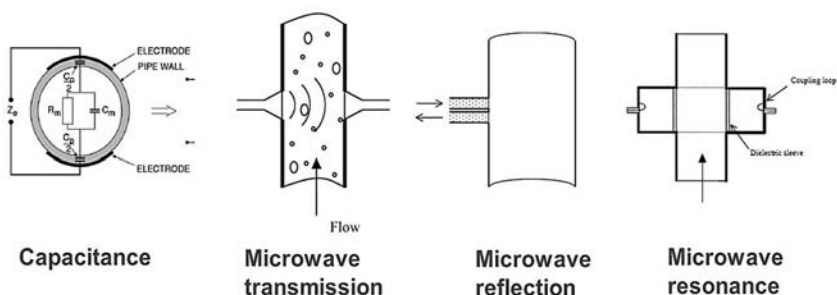


Fig. 4.2. Categories of water cut as described by Nyfors (2000) [20].

There are several possible ways to design and assemble microwave transmitters and receivers in a pipe according to the suitability of end application.

4.3.1.1. Transmission Sensors

In transmission based sensors in a pipe, the transmitter and receiver antenna are placed behind dielectric walls facing towards each other. The electromagnetic wave travels between the antennas while penetrating through the flowing media in the pipe. The complex permittivity of the media affects both the phase and the amplitude of the travelling wave [19]. The advantage of this arrangement is the simplicity and good sensitivity. But the main challenge is the complications in signal interpretation which is also influenced by reflections in various parts of the system, like the dielectric walls and other interfaces arising out of flow regimes. The reflections in the system may lead to difficulties in signal interpretation and can cause inaccuracy in estimation [20].

4.3.1.2. Reflection Sensors

In reflection based sensor system, amplitude and phase of the reflected wave from the end of the transmission line are measured [21]. The measurement principle is commonly based on the influence of flowing media on the fringing electromagnetic fields which are in direct contact with it. A common example is the open-ended coaxial probe, which is used for measuring permittivity over a broad frequency range [22, 23]. A disadvantage of reflection type sensors is the small sensing volume. Due to this, it is sensitive to drift due to deposits over it. Because of the small local sensed volume, it is not a suitable principle for inhomogeneous mixtures [24].

4.3.1.3. Resonator Sensors

The resonance frequency of a microwave resonator is related to the permittivity of the media in the resonator. By measuring the resonance frequency, the permittivity of the flowing media can be estimated [25, 26]. Resonance based measurements are quite sensitive to even small changes in permittivity, however, this can also be a disadvantage when the wide range is to be measured [27]. One of the distinct advantages of the resonator based sensor is that it is relatively robust as compared to amplitude and phase measurements. Because microwave resonators are inherently stable and the resonant frequency and quality factor (Q-factor), which are the two measurable properties of a resonance, can be measured with a high accuracy, the microwave resonance method is the most sensitive and accurate method available for measuring the Water Volume Fraction (WVF) of a wet gas flow [5, 25].

Microwave resonators can be arranged in several different ways inside a pipe. There are broadly two classes of resonator sensors a) strongly coupled to media b) weakly coupled to media. The former class is more suitable for materials with low losses. For water cut measurements, this generally means oil-continuous fluids. In case of highly lossy media, significant damping can result in the elimination of resonance. The resonators with a weak coupling to the media work better in such a case [25, 28]. In weakly coupled resonators, only a small fraction of the resonance fields are exposed to the media resulting in just a perturbation to the resonance resulting in a reduced sensitivity of the sensor. Nyfors

(2013) [47] described an arrangement where a dielectric resonator was used to sense just near the wall of the pipe.

4.3.2. Water Cut Estimation from Microwave Sensors

The Microwave based sensing principles often use a water cut estimation process as shown in Fig. 4.3. The other way is a direct calibration model from measurement to water cut developed in calibration facilities and applied in the field. But that approach suffers from bias when fluid properties of a field are different from that of calibration facility. Hence a model-based approach is better (Fig. 4.3). The measured microwave sensing parameters from the sensor at a single or multiple frequencies are used to estimate the media permittivity of the oil-water liquid mixture. The water permittivity (ϵ_w) and oil permittivity (ϵ_o) along with oil-water mixture permittivity (ϵ_m) are used in a mixture model to calculate water cut. Water permittivity can be calculated using the model developed by various researchers [29, 30] for known water temperature, salinity and the electrical frequency. There are several mixture models that can be used to relate permittivity of oil, water, the oil-water mixture to Water-Liquid Ratio (WLR) [31].

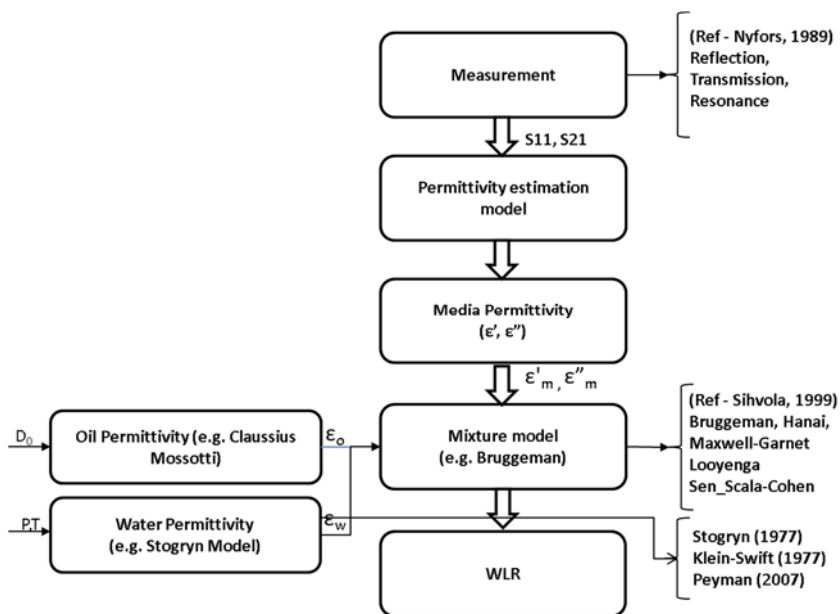


Fig. 4.3. Estimation process of water cut from microwave measurements.

4.3.3. Advances in Microwave Sensing Technology

One of the earliest developments on Radio Frequency based sensor was made by Dykesteen *et al.* (1985) [32] consisted 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 limit their usage for high accuracy requirements. Hammer *et al.* (1989) [10] demonstrated a helically shaped capacitance electrode system for water fraction in oil-water mixtures with repeatability better than 1.5 %. They also demonstrated that helically shaped electrodes are less dependent on variation in flow regimes. Demori *et al.* (2010) [33] 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 employs guard electrodes, coupled to a tailored electronic interface to drive the guard electrodes.

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 (2010) [34] 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 [35].

Thanks to the increasing availability of precise electronics, driven by developments in the telecom industry, microwave-based sensing solutions for robust and accurate WLR measurement have been emerging rapidly. Castle *et al.* (1974) developed one of the earliest microwave-based sensing systems for water fraction measurement in crude oil applications. Krupa (2006) [36] provided a comprehensive review of sensing methods for microwave in frequency domain.

Zarifi *et al.* (2016) [37] 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.

Oon *et al.* (2016) [28] 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 (2016) [38] 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 to 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 [39].

Al-Kizwini *et al.* (2013) [40] 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 [41].

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 [42]. Ni and Ni (1997) [43] described a class of non-intrusive microwave resonator sensors, called extra-cavity perturbation methods, for generic applications.

Jannier *et al.* (2013) [44] presented a microwave reflection method to measure the water content in oil. Microwave reflectometry is applied to multiphase flow metering in the context of oil extraction. The sensor consists of two open-ended coaxial probes operating at complementary frequencies (at 600 MHz and around 36 GHz) and was designed to resist harsh field conditions. This publication presents and comments on results obtained in realistic dynamic conditions, on a three-phase flow loop (water-oil-gas). The main conclusions are the following: Bruggeman and Hanai's mixing rule applies to natural emulsions and can be used to determine the composition of the water-oil liquid phase; results obtained for annular flows are very sensitive to small perturbations such as bubbles or waves at the liquid-gas interface; in the case of triphasic slug flows, the composition of the liquid phase can be estimated by proper filtering of the data.

Tan *et al.* (2015) [45] described an information fusion approach to measure multiphase flow parameters including water cut. They used a conductance ring sensor and combined it with pressure drop measurement for estimation. This work indicates a research trend of using multiple sensor data fusion to estimate the parameters of interest. Zhang *et al.* (2014) [46] also described a soft measurement estimation of water holdup based on neural network models.

In the patent by Nyfors (2013) [47], an open-ended cylindrical resonator is described for near wall measurement of water salinity in wetgas in a multiphase stream. In a wet gas flow, it is important to know the WVF because of the problems with hydrate formation, scaling, and corrosion caused by the water. Also, the salinity of the water, caused by the production of formation water, is a very important factor as it strongly affects both corrosion and the formation of scale.

The microwave resonance principle is based on measuring the permittivity / dielectric constant of the flow. Water, being a polar molecule, have a high permittivity (40-80) compared to that of oil (in the order of 2-3) or gas (~1) the permittivity of a mixture of these three constituents is dominated by the contribution from the water. Methods based on measuring the permittivity (microwave and capacitive methods) therefore provide the highest sensitivity for measuring the WVF of a mixture. Because microwave resonators are inherently stable and the resonant frequency and quality factor (Q-factor), which are the two measurable properties of a resonance, can be measured with a high accuracy, the microwave resonance method is the most sensitive and

accurate method available for measuring the WVF of a wet gas flow. However, when the WVF becomes very low, the permittivity of the mixture (i.e. the flowing fluid) starts to become dominated by the contributions from the oil and the gas. Especially the permittivity of the gas depends on the pressure and the temperature. To be able to resolve the contribution from the water one needs to know the contributions from the gas and the oil. For example, the invention described by Nyfors and Oystein (2005) [48] also uses the hydrocarbon composition and measurements of temperature and pressure as inputs, and models for calculating the permittivity of the oil and the gas. The accuracy of the measurement of the WVF is then limited by the accuracy of the models, and the accuracy of the measurements of the temperature and pressure.

Wylie *et al.* (2006) [49] developed an intrusive electromagnetic cavity resonator based sensor for multiphase flow measurement through an oil pipeline. This sensor is non-intrusive and transmits low power (10 mW) radio frequencies (RF) in the range of 100-350 MHz and detects the pipeline contents using resonant peaks captured instantaneously. The multiple resonances from each captured RF spectrum are analysed to determine the phase fractions in the pipeline.

Nyfors (2000) [5] developed a downhole water cut meter. This sensor is based on semi-sectorial resonance modes and is designed to measure the mixture ratio of oil and water in an oil well deep in the ground where the temperature and pressure are high. Because the space between the casing and production tubing is annular, the shape of the sensor was designed to match the spatial requirements in the annulus of an oil well. This resonance measurement method is not accurate when the sample is a high-loss material.

An example of a method for measuring properties of flowing fluids and a metering device and a sensor used for performing this method has been described in [5]. The sensor uses the microwave resonance principle for the measurement of oil-continuous fluids (water drops and gas bubbles in oil, i.e. the oil is a continuous phase) and the measurement of conductivity for water-continuous fluids (oil drops and gas bubbles in water, i.e. the water is the continuous phase, and is intended for installation in a production zone inside an oil well.

Another example of a method for measuring flowing fluids with a far higher gas content, i.e. wet gas (a wet gas flow is a multiphase flow with a high gas volume fraction, usually called the gas void fraction (GVF),

typically > 99 %) or high-gas multiphase flow, has been described in patent by [47]. This is also based on the microwave resonance so principle.

Huang (1998) [50] developed a transmission line model based on microwave theory to improve the calibration procedure of the water cut meter, Starcut. Through this microwave model and mixing law, the attenuation and phase shift of microwave signal can be directly related to water cut of oil-water mixture. This model uses empirical formulae to consider hole effect problem and did not include microwave energy leakage along sample pipe. This will result in inaccuracy of results from model prediction.

Folgero and Tjomsland (1996) [51] proposed open-ended coaxial probe to measure the composition of a well-mixed water-oil emulsion layer. The composition of this thin emulsion layer can be determined from permittivity measurements with this open-ended coaxial cable. Techniques for probe design and determination of liquid permittivity are also studied. They developed a bilinear model and an empirical exponential model to estimate the permittivity of thin liquid layers. This bilinear model needs calibration measurements on three samples with known permittivity. A full-wave model of the probe is also developed with lower precision, but this model need not be calibrated. A simple reference plane rotation is needed. This method also cannot be used to study characteristics of interior section fluids such as oil and water droplet shape, interface property and emulsion status.

Marrelli *et al.* (1996) [52] developed a microwave water cut monitor for field application and for the continuous measurement of the percent water in crude production streams over the entire 0 to 100 % range. This monitor can continuously report emulsion status (water-continuous or oil-continuous), effective NaCl salinity and effective paraffin carbon number of the hydrocarbon phase. Operator interaction is minimized by features such as automatic self-calibration, unattended operation at remote locations, remote access options through SCADA systems and self-starting after power outages. However, the calibration method of this monitor is to compare the data from the unknown sample with previously measured data which came from a known sample and were saved in the calibration database. Because of the complexity of multiphase flow, this calibration process may affect measurement results. Existing water cut predominantly depends on empirical data and correlations that are

sensitive to fluid properties. Correlation methods are therefore limited in their general applicability and require frequent re-calibration.

4.3.4. Research Challenges in Microwave Water Cut Metering

In recent years, significant technology advancement has been done for both MPFM and standalone water cut measurement. Several manufacturers have been continuously testing and maturing the technology and new suppliers are also rapidly coming up with novel solutions. However, it is a general consensus among industry experts that a universal meter is a challenge. A lot of improvement is still required to achieve accurate, reliable and robust MPFM and water cut metering. Below are a few known gaps in metering technology

4.3.4.1. Flow Regimes

The performance of MPFM and water cut meter is highly dependent on flow regimes they operate in. As the gas fraction increases above 90 %, the accuracy of the MPFM drops significantly. There are separate wetgas meters available which are especially suited to perform measurements at high GVF conditions (>95 %). The water cut measurement in high GVF is challenging due to a small liquid content in the flow [53, 54].

4.3.4.2. Periodic Calibration

MPFM and water cut meters suffer from changes in fluid compositions. Due to this, the fluid properties changes over a period of time resulting in the need for recalibration of the sensors periodically. Periodic calibration poses a logistic and operational constraint on operators [55, 56].

4.3.4.3. Oil Composition

The changes in oil composition over a period of time changes its physical and electrical properties resulting in deviations from values originally fed into the meter. Hence, the change in properties as viscosity, density and permittivity affect the accuracy of a meter [55-57].

4.3.4.4. Scaling and Fouling

Over time, scale can develop inside the meter spool surface which changes the sensor performance especially if a reflection type sensor is used in the meter. If a DP-Venturi is used, the coefficient of discharge can change due to scale [53]. Moreover, due to scaling the effective cross-section area available to the flow changes which the does not account for. These factors may lead to deviation in the accuracy of the meter. Wee *et al.* (2013) [58] demonstrated scale formation inside a meter after several years of field operation.

4.3.4.5. Dielectric Mixture Models

Dielectric mixture models can cause significant errors in relating measured signals to permittivity. These models often assume that the mixture is made up of simple geometrical inclusions like spheres, ellipsoids of droplet phase within a host (continuous) phase as described by Sihvola (1999) [31]. The non-linear behaviour of various mixture models are as shown in Fig. 4.4. They also often assume a homogenous distribution of the droplets in the host media. In the real field conditions, there may be significant deviations from the simplistic assumptions made by dielectric mixture models. This can be a potential cause of inaccuracy depending on the application. This is especially true in case of poorly mixed flows and is one of the reasons of installation of mixers before the meters.

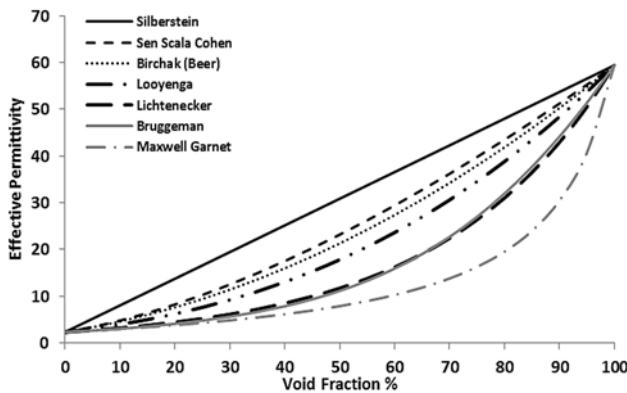


Fig. 4.4. Dielectric mixture models for a mixture of two dielectric materials. Void fraction is of the particle phase dielectric component (Shivola, 1999) [31].

4.3.4.6. Emulsion Transition Zone

The transition point of the emulsion type from water-in-oil (w/o) to oil-in-water (o/w) or vice versa is not well understood and is extremely hard to predict (Figs. 4.5, 4.6). This zone poses a big measurement challenge as the mixture properties are not well understood leading to poor performance of the meters [54].

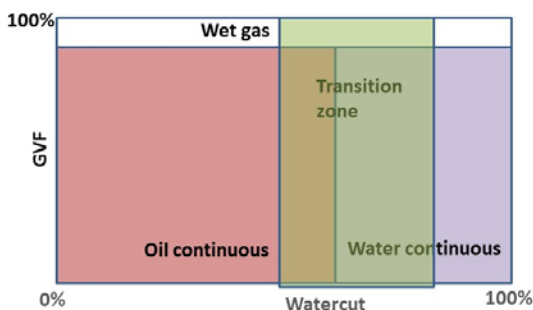


Fig. 4.5. Transition zone of the oil-water mixture is a measurement challenge.

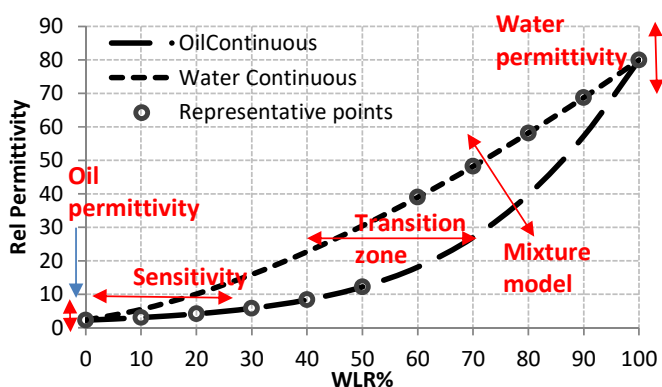


Fig. 4.6. A pictorial representation of a few factors causing water cut errors.

4.3.4.7. Salinity

Presence of salt alters the permittivity (Fig. 4.6) and density of aqueous phase and hence affects the estimation of water cut. In oil-in-water flow,

MPFMs need the input of water conductivity/salinity values in order to perform as per their specifications. Water-in-oil mixture has the much lesser influence of salinity change as compared to that of oil-in-water [53]. With a change in salinity over time, the meter readings tend to deviate from their correct values. Due to this, several research groups and manufacturers have been developing their own proprietary salinity sensors [17, 59, 60]. In case of microwave sensors, microwave transmission across a pipe may be significantly attenuated to measure. Hence, highly saline water in oil-in-water mixture poses a challenge for transmission based microwave sensors [61, 62]. Seraj *et al.*(2014) [60] reviewed the state-of-the-art in sensor technologies to measure salinity in multiphase production streams. Sactre *et al.*(2010) [63] demonstrated a dual-energy gamma based measurement system for salinity independent measurement. Somaraju and Trumpf (2006) [64] developed a model to estimate water dielectric properties with various salinities.

4.3.4.8. Hydrate Inhibitors

To prevent hydrate formation, a significant amount of thermodynamic hydrate inhibitors namely Methanol and Mono-Ethylene Glycol are injected at the well head. Since these are miscible in water, they are measured as water by the microwave as well as gamma-ray densitometers. These chemicals significantly affect the permittivity and density of water thereby affecting readings from the meters [55, 65]. Recent developments using Infrared Absorption have claimed to measure hydrate inhibitors in multiphase mixtures as well as independently estimate water cut [4].

4.3.4.9. Sensitivity at Low Water Cut

The sensitivity of water cut with respect to the permittivity of the oil-water emulsion at low water cut is quite low as compared to sensitivity at higher water cut (Fig. 4.6). This is challenging as the sensors should be designed to handle a wide dynamic range.

4.3.4.10. Heavy Oil

Heavy oil fields are has been increasingly adopting the use of multiphase flow meter but the performance and accuracy of meters are still not in desirable limits [66]. Due to the high viscosity of heavy oil, the flow

through the meter is more likely to be in the laminar region rather than turbulent. This may be difficult to validate in the field conditions and hence some of the key assumptions in meters may not hold true [55]. Moreover, the emulsion characteristics of heavy oil at field conditions are not well understood. Pinguet (2011) [57] described the challenges with Heavy oil metering and reviewed several measurement technologies.

4.3.4.11. Entrained Gas

A common problem encountered in oil well production testing is gas “carry-under” into the separated liquid stream. This results in a trace amount of gas entering the water-cut meter, producing errors in the water-cut reading [44]. Gas carry-under may be caused by high liquid viscosity, improper separator operation, a separator with a build-up of sand in the bottom, or poor separator design. These are some of the issues which significantly affect the allocation factors encountered in oil and gas operations. Multiphase measurement is typically performed on the surface, where pressures are relatively low. As pressures are reduced, gas dissolved in the oil is released. A reduction of pressure may cause gas to flash out of solution as crude oil flows from the separator. The amount of gas evolved depends on crude properties, operating temperature, pressure, and differences in pressure across the multiphase. Once entrained gas enters a water-cut meter, it will affect the reading regardless of the principle of operation. When a mass flow meter is used for water-cut measurement, the entrained gas will cause a decrease in density reading, which will be misinterpreted as a decrease in water percentage. The microwave water-cut meter, which operates based on the difference in dielectric constant of water (40 to 80), oil (2-3) and gas (1), will see a decrease in the dielectric constant of the flow stream when a small amount of gas is entrained.

4.3.4.12. Other Factors

There are several other chemicals which are injected at the well head as part of flow assurance strategies. These include emulsifiers, corrosion inhibitors, H₂S, CO₂ among others. Sand erosion can lead to erosion to the throat of venturi [55].

Table 4.2 shows the summary of the research gaps discussed.

Table 4.2. Summary table of water cut metering research gap.

Factors	Issues	Research Gaps	References
Flow Regimes	Flow regimes affect the accuracy of measurements	Effect of flow regimes on transducers	[53, 55]
Periodic Calibration	Drift in sensor demands periodic calibration	Field calibration, self-calibration	[56]
Oil Composition	Field variations of oil properties (viscosity, density, permittivity etc.)	Effect and mitigation on measurement techniques	[57]
Scaling and Fouling	Scaling and fouling over sensors affects accuracy in measurements	Effect and mitigation on measurement techniques	[58]
Mixture Models	Multiphase mixtures are often in-homogenous dielectric mixtures, may violate assumptions behind mixture models	Realistic mixture models derived for in-homogenous mixtures and larger inclusions	[31]
Transition Zone	Transition between mixture types affects accuracy of measurements	Insufficient understanding of transition zone between mixture types	[54]
Salinity	Field variations of water salinity affects meters accuracy	Methods to estimate salinity in multiphase flow in various mixture types	[53, 59, 60]
Hydrate Inhibitors	Flow assurance chemicals affects fluids properties leading to meter accuracy	Effect of Hydrate Inhibitors on multiphase fluid properties and compensation methods	[4]
Sensitivity	Non-linear mixture models shows poor sensitivity at lower water cut	Sensing methods capable of handling wide sensitivity range	[31]
Heavy Oil	Viscosity, mixture properties, flow characteristics in heavy oil affects meter accuracy	Insufficient understanding of heavy oil flow characteristics in field conditions	[65]
Entrained Gas	Entrained gas alters the liquid properties	Factors affecting entrained gas in field and separation challenges	[44]
Other Factors	Injected chemicals affects fluids properties, erosion, corrosion, sand, H ₂ S	Field factors altering meter characteristics in unpredictable ways	[55]

4.4. Summary

Water cut measurement technologies and methods are discussed and their gaps identified. Microwave based water cut measurement are gaining popularity in academic and industrial communities. Though the research trends indicate that microwave sensing technology is gaining attention and gaining maturity, there are several issues yet to be addressed for accuracy and robustness in field use. Microwave sensors are simplistically categorised into one of the following categories – transmission, reflection, resonance. However, a combination of reflection and resonance is explored only for limited applications in multiphase flows (wet gas, salinity) and the literature for applications in water cut measurements is very limited. There is a quest for microwave water cut sensing methods which are not affected or minimally affected by the presence of gas in the multiphase flow stream. Moreover, the sensing method should also address the low sensitivity of mixture permittivity at the lower end of water cut (also termed as a WLR in this work) and should ideally work in water continuous (oil-in-water) mixtures.

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