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INVESTIGATION OF TRACE AMOUNTS OF GAS

ON MICROWAVE WATER-CUT MEASUREMENT

A Thesis

by

JIN LIU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2005

Major Subject: Petroleum Engineering

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May 2005

Major Subject: Petroleum Engineering

ABSTRACT

Investigation of Trace Amounts of Gas
on Microwave Water-Cut Measurement. (May 2005)
Jin Liu, B.S., Southwest Petroleum Institute
Chair of Advisory Committee: Dr. Stuart L. Scott

In recent years, the upstream oil and gas industry has dealt with some of the most challenging metering applications. One of these is the measurement of water percentage at the point of allocation. It is an essential requirement when test separators or the newly developed full multiphase meters are utilized for oil well production testing. Water-cut can be obtained from measurement of differential pressure, capacitance/conductance, gamma rays absorption, absorption of infrared light, coriolis mass measurement, or microwave permittivity. The use of microwave permittivity has been shown to be very effective with the added benefit of not requiring a nuclear source, as is the case with a gamma ray densitometers. A common problem encountered in oil well production testing is that of gas "carry-under" into the liquid stream exiting the test separator. This results in a trace amount of gas entering the water-cut meter, producing errors in the water-cut reading. Gas carry-under may be caused by high liquid viscosity, improper separator operation, or poor separator design. Gas carry-under is believed to be one of the major causes of large allocation factors in oil and gas operations.

Problems in clearly defining the three-phase stream as to flow regime and actual gas bubble size have been described in the technical literature. Pertinent references are discussed and compared. The issues in trying to perform such tests in the laboratory and the correlation of the data are disclosed and the difficulties in trying to correlate the effects of the entrained gas are described.

Field testing and experience by at least one manufacturer of equipment has verified the effect of entrained gas, but little quantitative data relating gas-cut to increased error of measurement has been published. The objective of this work was to investigate the performance of a microwave water-cut analyzer under three-phase flow conditions to determine the impact of the presence of gas in the liquid stream.

Experiments were performed that investigated the effects of entrained gas on a commercial water-cut analyzer. These tests were conducted at the Texas A&M Tommie E. Lohman Fluid Measurement Laboratory at low pressure conditions (< 40 psig). The test fluids were air, water and two types of oil: mineral oil and hydraulic oil. These experiments investigated oil continuous emulsion conditions with the Gas Volume Fraction (GVF) ranging from 0-25% and the water-cut ranging from 5-30%. Liquid flow rates were between 500-3,700 bbl/day. A 2-inch water-cut full range meter was utilized for these tests. The error in water-cut was seen to increase with increasing GVF ranging from 0% to 25%. However, the measurement remained stable over the entire range of tests. A correction was developed to correct water-cut meter readings based on the amount of gas in the liquid stream.

ACKNOWLEDGEMENTS

I am grateful to Dr. Stuart Scott, chair of my advisory committee, for devoting his time to discussion of my work. Dr. Scott continuously added fresh ideas and experienced judgment to my efforts. His work on this topic is the foundation of this thesis.

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CHAPTER I
INTRODUCTION

1.1 Application of Water-Cut Measurement

In recent years, some of the most challenging metering applications have developed in the upstream oil and gas industry. The traditional measurement approach for produced fluids could take several hours to have phase separation and independent measurements for each oil, water, and gas phase. If the fluid components are easily and fully separated, this approach works well. However, the traditional approach produces a large error in the measurement when the production fluid contains a tight emulsion or foam.

The oil and gas industry has found a lot of advantages in multiphase developments, including reducing capital costs, accessing remote locations, reducing environmental impacts and continuous real-time monitor. These developments often require a multiphase flow meter which is compact, light weight and can measure the flow rates continuously.

Most oil wells produce same amounts of water along with the oil. This produced water is expensive to transport, tends to be corrosive to processing equipment, and most importantly the water has no value. However, environmental impact and health issues require companies to monitor water-cut in produced water stream prior to dispersal. In addition, it is very important to carefully monitor the water content of crude oil stream.

This thesis follows the style and format of the *Journal of Petroleum Technology*.

Water-cut measurement is one of the most challenging multiphase measurements. It is essential when two-phase test separators are used for oil well production testing. Water-cut measurement is also an essential component of many multiphase meters, which are used to help determine production rates, and in some case to perform, custody transfer measurements[1].

Water-cut can be obtained in a variety of ways, for example, from measurement of differential pressure, capacitance/conductance, gamma rays absorption, absorption of infrared light, coriolis mass measurement, or microwave permittivity. The use of microwaves has been shown to be very effective with the added benefit of not requiring a nuclear source, as is the case with gamma ray densitometers.

With flow meters measuring the individual oil and water flow rates, water-cut meters are being applied in oil/water two-phase flow. They can be installed either downstream of the two-phase separator or in the well stream for oil / water two-phase flow.

In recent years, significant development has taken place in the area of water-cut measurement. A variety of manufacturers have developed a degree of maturity in applying varied measurement and fabrication techniques for water-cut meters. However, a lot of improvement is still required, as inaccurate water-cut measurements will reduce an operator's ability to optimize well production within a given production facility.

Many questions were answered during the 1989 field testing of a microwave water-cut meter at ARCO's Flow Station No. 2 in Prudhoe Bay, Alaska[2]. The results of these tests showed that a microwave water-cut meter can give excellent results in the oilfield environment and the meter also can measure the water-cut of fluids that include up to 5% of entrained gas with acceptable errors. Accurate water-cut measurements were found to add benefit in terms of potential savings in capital expenditure.

1.2 Problem Description

A common problem encountered in oil well production testing is gas "carry-under" into the liquid stream. This results in a trace amount of gas entering the water-cut meter, producing errors in the water-cut reading. Gas carry-under may be caused by high liquid viscosity, improper separator operation, a separator with a buildup 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 components[3, 4].

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 (68 to 80), oil (2.5) and gas (1), will see a decrease in the dielectric constant of the flow stream when a small amount of gas is entrained.

1.3 Objective of This Work

In recent years, there has been a general realization that accurate well test meters can have a large economic impact on oil and gas developments. This has driven the development of high accuracy water-cut measurement in oil and gas industry.

Field and laboratory testing and experience have investigated the effect of entrained gas[1,5,6,7,8,9,10], but a review of literature reveals that only a few authors have shown data relating gas-cut to increased allocation factors which is fraction of total production from a system attributable to an individual well. The objective of this work is to investigate the performance of a microwave water-cut meter under three-phase flow conditions to determine the error in the water-cut measurement introduced by the presence of gas in the liquid stream.

CHAPTER II
WATER-CUT MEASUREMENT TECHNOLOGY

Water-cut is defined as the ratio of the volumetric flow rate of water to volumetric flow rate of the total liquid expressed as a percentage. The technology and the operation of water-cut devices is still of great interest to the oil and gas industry. Over the years a number of technologies have been developed with varying degrees of success. This section describes the various approaches taken for water-cut measurement.

2.1 Water-Cut Measurement

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. First it can not provide a continuous measurement. In addition, this method is time consuming, the accuracy is questionable, and personnel are exposed to hazardous chemicals. Note that he 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.

2.1.2 Differential Pressure

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,

$$\Delta P_g = gL\left[\rho_w WC + \rho_o \left(1 - WC\right)\right] \quad \text{(2.1)}$$

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 Eq. (2.1) when the oil water densities are known.

This is a very simple and low cost method, only requiring a commercially available differential pressure transducer. 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 on room temperature with no solution gas. This density can be very different from that of flowing live crude oil.

2.1.3 Mass Flow Meter

Mass flow meters have found wide applications in the oil and gas industry in the past decade. Most modern installations utilize mass flow meters based on the coriolis principle. This is due to the accuracy of these meters and the added benefit of measuring flowing density in addition to the mass flow rate. A typical coriolis force flow meter 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 desntity:

$$\rho_{\mathrm{m}} = \rho_W WC + \rho_O (1 - WC) \quad \text{..................................(2.2)}$$

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.

2.1.4 Infrared Technique

This is a technology based on the bulk transmission of infrared radiation through an oil-water mixture. 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 (**Fig. 2.1**).

Since the infrared meter detects the oil rather than water, it's accuracy will improve as the water content increases. In oil/water two-phase flow, with water-cut ranging from 85 to 100%, the accuracy of infrared meter was within +/- 1.5% absolute. In oil/water/gas three-phase flow, with GVF ≤ 25% and high water-cut (greater than 90%), the accuracy of infrared meter is +/-2% absolute[8]. This meter will produce large errors (up to 20% absolute) as water-cut decreases. Also the meter doesn't have the ability to perform detailed compositional analysis, it can only distinguish between relative volumes of oil and water. Therefore, it is strongly recommended that this meter should always be installed with a mixer upstream[6].

The Infrared water-cut meter is a full-range water, and it is unaffected by transition from oil-continuous phase to water-continuous phase.

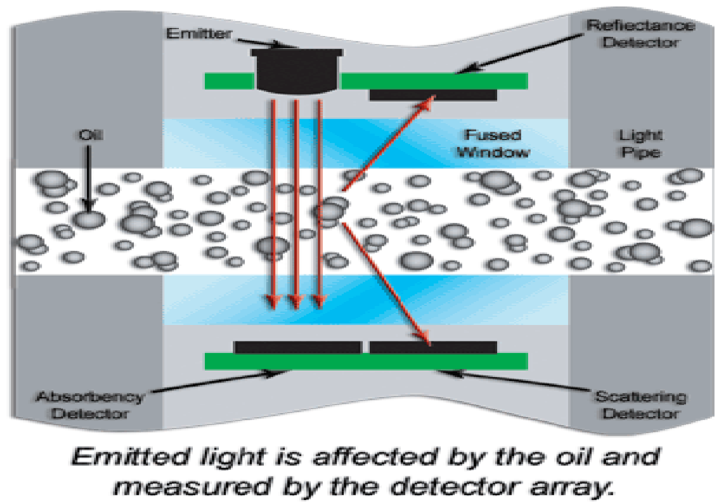

Fig. 2.1- Principle of Infrared Water-Cut Meter Operation (EP Solution Website)

2.1.5 Gamma-Ray Absorption Method

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 Eq. (2.3):

$$I = I_i \exp[-\mu z] \qquad (2.3)$$

where μ is the mass absorption coefficient, and z the distance traveled 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 from the following Eq. (2.4)[11]:

$$I = I_i \exp\{-(\mu_o \rho_o f_o + \mu_w \rho_w f_w + \mu_g \rho_g f_g)d\} \qquad (2.4)$$

where I_i is the intensity of gamma-ray with the pipe empty; μ, 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; subscripts o, w and g respectively refer to oil, water and gas; d is the internal diameter of the pipe, and

$$f_o + f_w + f_g = 1 \qquad (2.5)$$

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 are measured at two different energy levels. By performing measurements at two different gamma-ray energies, equation (2.4) can be used twice with different values of mass absorption coefficients. The volume fraction for 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.

This method for the oil, water, and gas fraction determination can be clearly demonstrated by using a cross plot of the resultant count rates, as shown is **Fig. 2.2**. The mixture attenuations at two different energy levels are compared to the attenuations of pure oil, water, and gas. From this cross plot, the fraction of each phase can extracted.

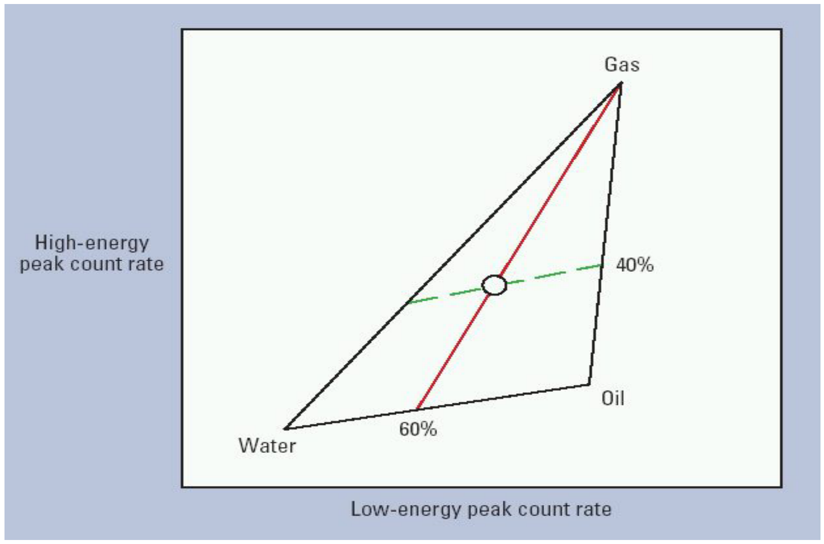

Fig. 2.2- Phase Fraction Measurement with Dual-Energy Gamma Ray Method (Schlumberger Website)

2.1.6 Capacitance/Conductance Method

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. A typical capacitance probe uses a cell composed of two plates or an open circuited center rod with a circular pipe as the outside element. Fluid flows through the space separating the inner and outer electrodes.

This 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. The dielectric constant is a dimensionless number; it simply expresses the ability of a material to be polarized and therefore store 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.

Analyzers 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 analyzers 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[3]. In most cases, the highest water-cut of the oil-continuous emulsion occurs at about 35-60%[3].

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% [9]. 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 a 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.

2.1.7 Microwave Principle

Microwave measurement includes the following basic setup: generation of microwave signals and detection of the microwave signals, and calculation of the water-cut results. The measurement can be frequency, wavelength, impedance or attenuation.

The dielectric constant and conductivity of water are much higher than that for oil. Permittivity is defined as a relationship where the real portion is energy storage (or dielectric constant) and the imaginary portion is the energy loss portion. The energy loss can be from three factors, dielectric rotational loss, interface polarization loss and resistive (ionic conductivity) loss[12]. This large difference in oil and water parameters can be utilized to measure water content of oil/ water mixtures. Currently, there are three commercial products using different microwave principles. A brief description of each method is given below, with additional detail given in Chapter III.

Roxar: For this type of commercial meter, the microwave dielectric properties of mixtures are an be measured using the electromagnetic resonant cavity method[7] (see figure on p.22). The water-cut meter is constructed such that the electromagnetic waves transmitted into a particular flowing mixture will, at a characteristic frequency (wavelength), resonate to produce distinct peak amplitude. This peak corresponds directly to the water content of the mixture and the characteristic resonant frequency is inversely proportional to the square root of the mixture dielectric constants[11].

The difficulty in the resonant cavity measurement technique is that it becomes inaccurate when the energy loss portion of the permittivity becomes significant[11]. The shift in the resonance frequency of the cavity becomes very difficult to predict when the imaginary part of the permittivity becomes dominant.

This water-cut meters measure the percentage of water in oil, water in condensate, and water in Natural Gas Liquid (NGL's). The most common is to measure the water content of crude oil.

Agar: This commercial device measures the concentration of the two fluids through the transmission of electromagnetic waves. One transmitter is used for transmitting a signal and two receivers for receiving a signal. The use of two receivers provides two output signals to determine the concentration. It measures the bulk dielectric properties of the fluids by signals received from two antennas spaced at different distances from a single source transmitter operating at 2.5 Gigahertz[13]. This water-cut meter measures over full range of 0-100% water-cut, regardless of the continuous phase (see figure on p.26). Typical application of this meter is for finished products, water in produced oil, and oil in the waste water process.

The major problem with this device is that the fluid at the surface of the insulator dominates the effect, in particular when the fluid consists of two immiscible fluids such as water with a few drops of oil. If this mixture is not homogeneous, the droplets change size or coating thickness varies, greatly affecting by the load[14].

Phase Dynamics: Another commercial water-cut meter is based on the oscillator load pull principle patented by Phase Dynamics, Inc (see figure on p.25). In this case, the oscillator (microwave source) is isolated from the load and as the fluid permittivity changes the result is a change in the operating frequency of the system. The advantage of this method is that it can produce 100 to 1000 fold increased measurement sensitivity over conventional microwave techniques[2,15].

Since the dielectric constant of water (68-80) and oil (2.5) are very different, water content can be determined. When the water content changes, the electronics on the end of the measurement section send an electrical signal. This wave will change position within the measurement section, and then the microwave oscillator will automatically detect the change in wave position and changes its basic frequency to create a standing wave in the measurement section. The sending and the receiving portion of the electronics are the same. They change the frequency to create a standing wave in the measurement section based on water content.

The accuracy of microwave measurement is affected by the salinity, density and temperature of the fluids. The viscosity and velocity of the fluids are only a factor in determining the emulsion size and maintaining a well mixed and homogeneous stream. The field calibration and/or prior knowledge of the fluid properties, such as density and salinity, are required to attain the specified accuracies. When properly applied microwave measurement of the water fraction is performed by evaluating the bulk dielectric properties of the fluid stream, this makes it less sensitive to surface deposits such as wax and paraffin until they become a significant fraction of the area of measurement.

2.2 Dielectric Properties of Emulsion

An emulsion is a mixture of two mutually immiscible liquids, one of which is dispersed as droplets in the other. The droplets which are surrounded by the continuous phase are called the discontinuous or internal phase[5]. When the volume fraction of one phase is very small compared to the other, the phase which has the smaller fraction is the dispersed phase and the other will form the continuous phase. There are two types of emulsions: O/W for oil-in-water (water continuous) emulsions and W/O for the water-in-oil (oil continuous).

Oilfield emulsion are characterized by a number of properties including appearance, basic sediment and water (BS&W), droplet size, bulk and interfacial viscosities, conductivities etc[16]. The droplet size distribution of an emulsion depends on a number of factors including the interfacial tension (IFT), shear, nature of emulsifying agent, presence of solids, and bulk properties of oil and water[16]. Droplet size distribution in an emulsion determines the stability of the emulsion. Generally an emulsion that has smaller size droplets will be more stable, the droplet size distribution also affects emulsion viscosity; it is higher when droplets are smaller.

Films that form around the water droplets at the oil-water interface stabilize produced oil field emulsions. These films result from the adsorption of high molecular weight polar molecules that are interfacially active[16]. By reducing interfacial tension and increasing the interfacial viscosity, these films enhance the stability of the emulsion. Highly viscous interfacial films can provide a mechanical barrier to coalescence and retard the rate of oil film drainage during the coagulation of the water droplets.

Emulsions are special liquid-in-liquid colloidal dispersion. Small droplet size and the presence of an interfacial film around water droplets affect their kinetic stability. Produced oil-field emulsions are classified based on their degree of kinetic stability as follows[16]:

- Loose emulsions: will separate in a few minutes.
- Medium emulsions: will separate in a matter of tens of minutes.
- Tight emulsion: will separate (sometimes only partially) in hours or even days.

Dielectric constant is a way to expressing the materials ability to retain electrical charges. It is a basic electrical property of matter for which oil and water have distinctly different characteristics. It is measured in units of farads per meter. Microwave water-cut meters use the big difference dielectric constant between the water and the oil to determine the water content even when an emulsion is present.

2.3 Theoretical Dielectric Constant Calculation

Numerous experimental and theoretical studies have been made to express the dielectric constant of a composite system in terms of its constituent phases and their compositions. The earliest attempt to calculate the dielectric constant of a dispersion of spherical particles by mathematical analysis was made by Rayleigh[12] (Eq.2.6). Most later models, like Wagner's equation and Bruggeman's equation, derived from Rayleigh equation and have been used to calculate the mixture dielectric constant in commercial application. Eq. 2.6 expresses the composite liquid dielectric constant, ε_L, in terms of the dielectric constant of the dispersed and continuous phases:

$$\varepsilon_L = \varepsilon_C \left[1 + \frac{3WC}{\dfrac{\varepsilon_D + 2\varepsilon_C}{\varepsilon_D - \varepsilon_C} - WC - 1.65 \dfrac{\varepsilon_D - \varepsilon_C}{\varepsilon_D + \frac{4}{3}\varepsilon_C} WC^{10/3}} \right] \quad \text{......................(2.6)}$$

The water-cut is given by WC and the dielectric constant of the dispersed phase is denoted by ε_D and the continuous phase by ε_C.

For a dilute dispersion, where $WC \ll 1$, Wagner derived the following equation for a random distribution of spherical particles with a uniform radius. The theoretical model used by Wagner is limited to small concentrations of the dispersed component[5].

$$\frac{\varepsilon_L - \varepsilon_C}{\varepsilon_L + 2\varepsilon_C} = WC \times \left[\frac{\varepsilon_D - \varepsilon_C}{\varepsilon_D + 2\varepsilon_C} \right] \quad \text{……………………………(2.7)}$$

Bruggeman developed a theory for concentrated disperse system on the basis of Wagner's theory and built following equation[5]:

$$\left(\frac{\varepsilon_L - \varepsilon_D}{\varepsilon_C - \varepsilon_D} \right) \left(\frac{\varepsilon_C}{\varepsilon_L} \right)^{\frac{1}{3}} = 1 - WC \quad \text{…………………………(2.8)}$$

Roxar full range water-cut meter uses Bruggeman's equation to calculate different water content. The following graph (**Fig. 2.3**) shows the dielectric constant calculated for a two-phase system using the Wagner's model and Bruggemen's model. As water-cut decrease, it can be observed that there is little difference between these two models.

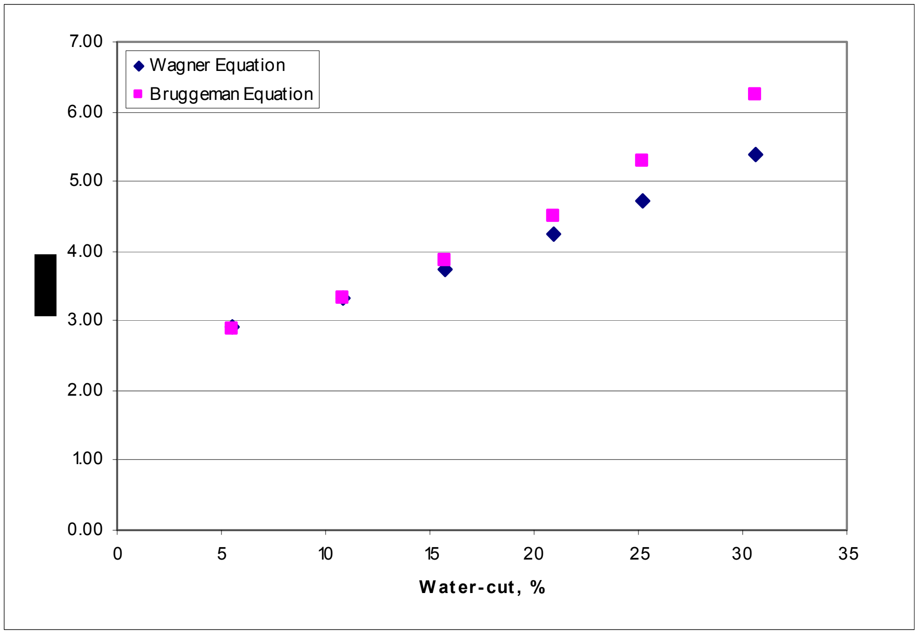

Fig. 2.3- Dielectric Constant Difference between Two Difference Theory Models

Wagner's equation will be used to examine two-phase test results in this work. When Wagner's equation (Eq. 2.7) is applied to a at water/oil system with oil as the continuous phase, Eq.2.7 becomes:

$$\frac{\varepsilon_L - \varepsilon_O}{\varepsilon_L + 2\varepsilon_O} = WC \times \left[\frac{\varepsilon_W - \varepsilon_O}{\varepsilon_W + 2\varepsilon_O} \right] \quad \text{.................................(2.9)}$$

here, ε_O refer to oil phase dielectric constant

ε_W refer to water phase dielectric constant

ε_L refer to mixture phase dielectric constant

Once enter *WC* and the dielectric constant for oil and water are known, we can predict ε_L.

2.4 Previous Work of Entrained Gas Effects on Measurement

In recent years, multiphase metering techniques have matured, and found wide application in the oil and gas industry as multiphase flow has become increasingly important for economic transportation of well streams from reservoir to process. At the same time, the oil and gas industry have also realized the importance of accurate well test measurements. The need for reliable design methods for multiphase flow has been the driving force, especially for gas-liquid flow. Many methods have been adopted: partial separation before measurement, adding demulsifier chemical to break tight emulsions, increasing the pressure at the measurement point to prevent the solution gas from going to free gas, and addition of a gas eliminator before measurement.

Partial Separation: One of the effective approaches for oil rate measurement is partial separation. Traditional separation methods use bulky vessels to completely separate the phases, while a compact separator is utilized to concentrate the oil phase to improve the accuracy of this measurement. A cyclone device is typical of these compact separators. A cyclone uses tangential acceleration of the multiphase mixture to create an artificial gravity environment. The cylindrical cyclone separator is used to strip off most of the gas phase from liquid stream. Under the correct condition, these compact separators can produce a 95% or more gas phase exiting the gas leg of the separator and a 95% or more liquid phase exiting liquid leg[9, 17, 18].

Demulsifier Chemical: Most test separators are practically designed to remove all entrained gas from the liquid. However, in some production situation, extremely tight emulsion can occur in the production line and test separator. Tight emulsions are characterized by unusually high viscosities, sometimes many times more than the crude oil viscosity[16]. Separating the entrained gas from this emulsion is not efficient even with a large test separator. Demulsifier that break the tight emulsion and have been found to be effective and practical.

Prevention of the Solution Gas: One way to minimize dissolved gas breaking out of the oil phase is to install the measurement meter below the separator. In a properly designed system, the static head effectively offsets the dynamic pressure loss in the flow line. This results in a higher pressure at the analyzer than at the separator, thus preventing solution gas from flashing. The design criterion (2.6) is expressed as[3]:

$$\Delta P_s > \Delta P_p + \Delta P_m \qquad (2.10)$$

The frictional pressure loss (ΔP_p) can be minimized by installing the sensor close to the test separator and using larger-diameter connecting pipes. Between separator and meter, the piping elements, such as tees, elbows, and reducing unions should also be minimized. Other devices such as sampling ports, static mixer, meter proving connections, dump valve, back pressure regulator should be installed downstream of the meter[3].

Gas Eliminator: When wellhead pressures are below the bubble point pressure, a certain amount of gas will be present in the production stream. Several producers have found adding a low cost in-line gas eliminator very effective[3].

CHAPTER III
MICROWAVE WATER-CUT METER

3.1 Roxar Full Range Water-Cut Meter

3.1.1 Principle of Operation

By measuring the dielectric constant of the mixture, the Roxar Water-Cut Meter determines the water content. As described before, this meter uses the electromagnetic resonant cavity method to measure the microwave dielectric properties of mixtures[7] (**Fig. 3.1**). A resonant cavity is a metal structure. Within the cavity the structure confines an electric field and causes it to reflect back and forth. This water-cut meter is constructed such that the electromagnetic waves transmitted into a particular flowing mixture will, at a characteristic frequency (wavelength), resonate to produce a distinct peak amplitude. This peak corresponds directly to the water content of the mixture and the characteristic resonant frequency is inversely proportional to the square root of the mixture dielectric constants.

Fig. 3.1- Roxar Full Range Water-Cut Meter

(Roxar Website)

3.1.2 Typical Operation

Roxar Full Range Water-Cut Meter is constructed as a coaxial resonant cavity. The pipe through which the mixture fluid passes, is used as the outer conductor of a coaxial transmission line, and in the middle of the pipe a metal rod is used as the centre conductor (**Fig. 3.2**). The meter includes one microwave device which measures the electrical properties of the flowing mixture, and a temperature sensor which measures the temperature of the mixture. The measurement device and temperature sensor are connected to a computer processor and provide signals corresponding to the measured dielectric constant and temperature values[11].

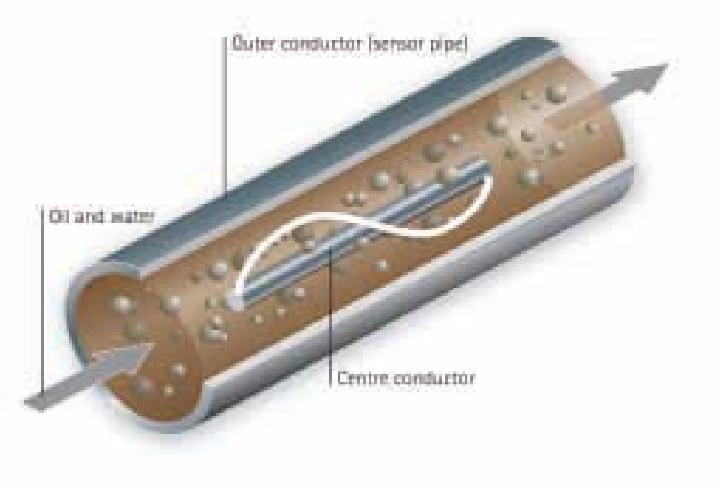

Fig. 3.2- Typical Measurement Operation of Roxar Full Range Water-Cut Meter (Roxar Website)

Through use of an open circuitry, created by cutting off the centre rod at both ends, the rod is made to resonate. At either end of the rod, the electric field propagating down the coaxial line will be reflected[11]. When an oil-water mixture is flowing in the space between the centre conductor and the pipe, the sensor resonates at the frequency dictated by the mixture. The signals are transmitted to the computer processor which determines the individual electrical properties of oil and water, respectively, at specific temperature.

These values are used together with the measured electrical properties to determine the water content using Eq. (2.8).

As we know, oil and water emulsions have two distinct types, O/W emulsion and W/O emulsion. The electrical properties of these two types are quite different even if the water content is identical, **Table 3.1** shows the mixture dielectric constant at different water-cuts for O/W type emulsion[11]. Without determining emulsion type, the potential accuracy of device will be reduced. Roxar Water-Cut Meters have defined a method to determine the emulsion type which increases the measurement accuracy. They have developed the following procedure to obtain the water content.

Table 3.1- Mixture Dielectric Constant[11]

Dielectric Constant	%WC (O/W)	%WC (W/O)	Difference
2.0	0	0	0
3.0	13.8	3.8	9.9
4.5	26.1	8.4	17.8
6.0	34.2	12.2	22.1
8.0	41.8	16.6	25.3
10.5	48.7	21.4	27.3
14.0	55.8	27.5	28.3
18.0	61.8	33.7	28.1
22.0	66.6	39.4	27.1
33.0	76.3	53.4	22.9
39.0	80.5	60.3	20.2
45.0	84.1	66.8	17.3
52.0	87.9	74.0	13.9
62.0	92.7	83.7	8.9
80.0	100.0	100.0	0

Step 1: Measure the mixture emulsion's dielectric constant and temperature.

Step 2: Determine the dielectric constant of water and oil at temperature.

Step 3: Use following Bruggeman equation to calculate different water content (%WC) corresponding to oil-continuous and water-continuous.

$$\left(\frac{\varepsilon_L - \varepsilon_D}{\varepsilon_C - \varepsilon_D}\right)\left(\frac{\varepsilon_C}{\varepsilon_L}\right)^{\frac{1}{3}} = 1 - WC_D \text{ ....(3.1)}$$

Applied to water-continuous emulsion, the equation becomes:

$$\left(\frac{\varepsilon_L - \varepsilon_o}{\varepsilon_w - \varepsilon_o}\right)\left(\frac{\varepsilon_w}{\varepsilon_L}\right)^{\frac{1}{3}} = WC_w \text{ ....(3.2)}$$

For oil-continuous emulsion, the equation is:

$$\left(\frac{\varepsilon_L - \varepsilon_w}{\varepsilon_o - \varepsilon_w}\right)\left(\frac{\varepsilon_o}{\varepsilon_L}\right)^{\frac{1}{3}} = 1 - WC_w \text{ ....(3.3)}$$

Step 4: Comparing the oil-continuous water content to an upper threshold limit (an appropriate threshold level would be 70% water[11]), determine whether oil or water is the continuous phase. If the measured mixture dielectric constant is greater, the mixture is determined to be water-continuous and the water content is set to the water-continuous solution, %WC (W/O), if the measured mixture dielectric constant is less, the mixture is determined to be oil-continuous and the water content is set to the oil-continuous solution, %WC (O/W).

For example, if the mixture dielectric constant is measured to be 10.5. The water content assuming oil-continuous and water-continuous are 48.7% and 21.4%, respectively. The mixture dielectric assuming oil-continuous is seen to be less than 70%, so mixture is determined to be oil-continuous and water content is 48.7%.

As another example, the mixture dielectric constant is measured to be 39.0. The water content assuming oil-continuous and water-continuous are 80.5% and 60.1%, respectively. The mixture dielectric under water-continuous is greater than 70%, therefore the mixture is determined to be water-continuous and water content is 60.1%.

3.2 Agar Full Range Water-Cut Meter

3.2.1 Principle of Operation

Fig. 3.3 shows the conduit and measuring system of Agar water-cut measurement. The transmitter (2) transmits a high frequency signal to an antenna, which is insulated from the fluid by means of an insulator (5). Impedance of the fluid acting on antenna (4) will vary with the electrical properties of the fluid which will affect the amount of transmitted energy. Receivers (7 & 9) are connected to similar antennae (6 & 8), which are spaced from the transmitting antenna (4), A divider (10) divides the outputs of receivers (7) and (9) and supplies a linearized output. The phase difference between the two receiving signals, can be used to measure the concentration of the two measured substances by transmitting at a specific frequency (about 2.45GHz)[14].

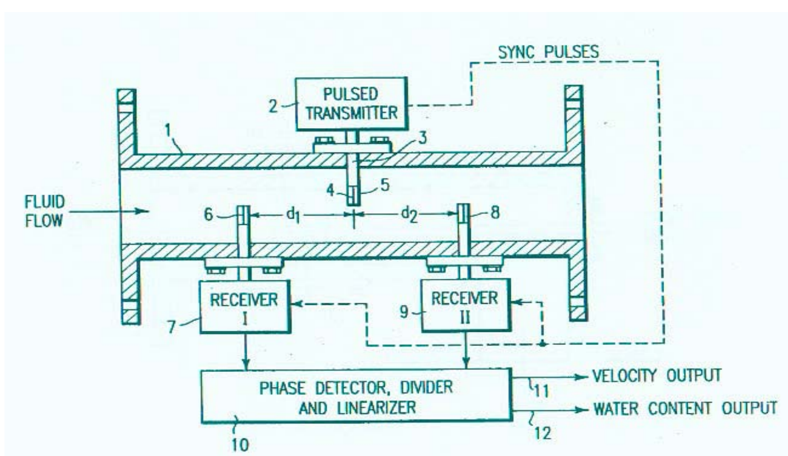

Fig. 3.3- Conduit and Measuring System of Agar Water-Cut Measurement[14]

The Agar Water-Cut Meter (**Fig 3.4**) measures the ratio and/or the phase difference of the powers received by each receiver (7) and (9). As both antennae (6) and (8) are exposed to the same fluid in exactly the same way, by taking phase difference of these signals, output (12) becomes independent of surface coating, etc, also as oil absorbs very little energy while water does, the amount of power received in each antenna is a function of the water content and the distance from the transmitting antenna[14].

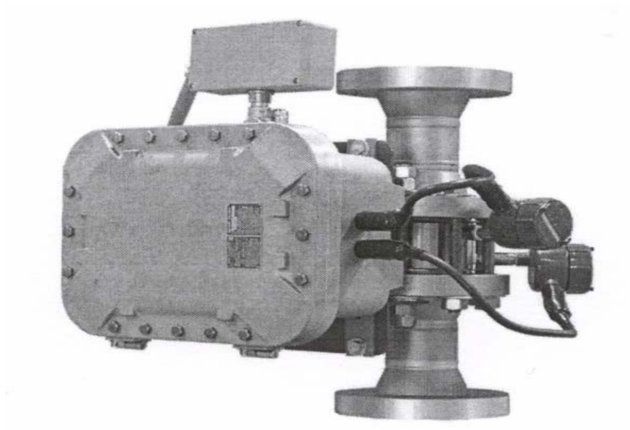

Fig. 3.4- Agar Full Range Water-Cut Meter

3.2.2 Typical Operation

Agar Water-Cut Meter measures the energy absorption properties of the oil/water mixture, and then yields a current output. The output data can be plotted on one of two distinct, empirically or theoretically derived data curves. One of the data curves is at oil-continuous phase and the other is at water-continuous phase. A comparator is used to determine whether it is at oil-continuous phase or at water-continuous phase, and select the proper energy absorption data curve. Each of these curves is a plot of water content against the energy absorption properties of the fluid plotted.

Agar Water-Cut Meters have following procedure to obtain the water content as described in their patent[19].

1. An oil/water monitor measures the electrical properties of the mixture flowing through pipeline;

2. The oil/water monitor generates the current or electrical signal transmit to a zero-&-span adjuster**;**

3. From the zero-&-span adjuster**,** the data is transmitted from analog to digital at converter and calculator and to a comparator.

4. The comparator uses this information to select one of two memories: a water-continuous phase memory or an oil-continuous phase memory. Normally the comparator will be a microprocessor or other computing device which compares the measured electrical signal with a predetermined value.

5. The calculator also receives a velocity signal "v" from a digitizer which digitizes an analog signal received from a flow meter in the pipeline. Additionally, the digitizer and the calculator may also receive a temperature signal from a temperature measuring device disposed in the pipeline.

6. The water-continuous phase memory and the oil-continuous phase memory are programmed with families of predetermined curves which are empirically or theoretically.

If the measured current is greater than the predetermined value, water is in the continuous phase and the comparator selects the curves set on the water-continuous phase side. If the measured current is less than the predetermined value, then the oil is in the continuous phase and the comparator selects the curves set on the oil-continuous phase side.

7. Depending on which continuous memory is selected, the amounts of current at particular phase memory determine the percentage of water content by the way of the respective curve. The digitized data representing the percentage of water is then transmitted to a multiplier, and to a digital-to-analog converter. The data from the digital-to-analog converter is then transmitted to a meter, and then the water content can be directly read from this meter.

3.3 Phase Dynamics Water-Cut Meter

3.3.1 Description of the Meter

The Phase Dynamics Analyzer measures the percentage of water in a flowing hydrocarbon liquid stream. The measurement technique is based on a principle known as oscillator load pull.

The system typically consists of three components as shown in **Fig. 3.5**[15]:

- A measurement section
- An electronic unit
- A system cable connecting the two.

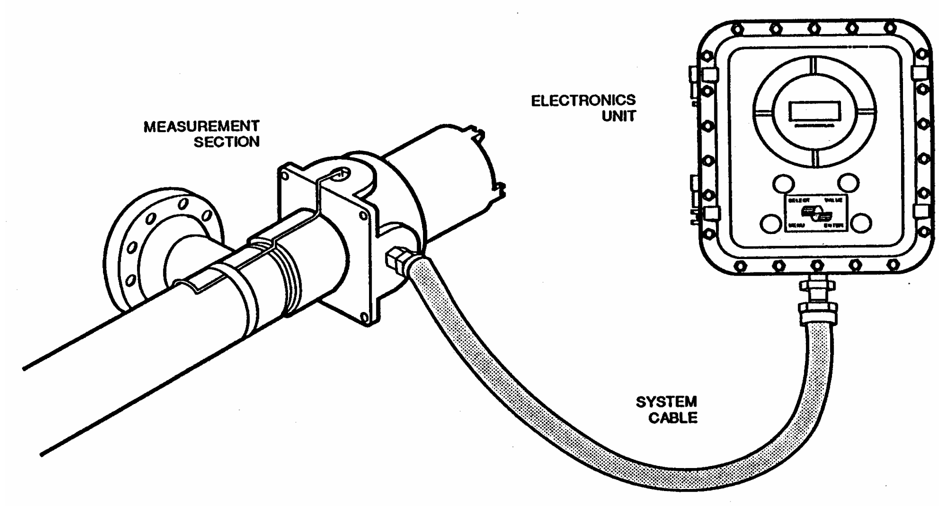

Fig. 3.5– Phase Dynamics Load-Pull System for Measuring Water in Hydrocarbons[15]

The measurement section is an assembly of:

- A pipe section
- A temperature sensor
- A microwave oscillator module mounted in a protective enclosure

Figs. 3.6A and 3.6**B** show the internal and outer view of the measurement section

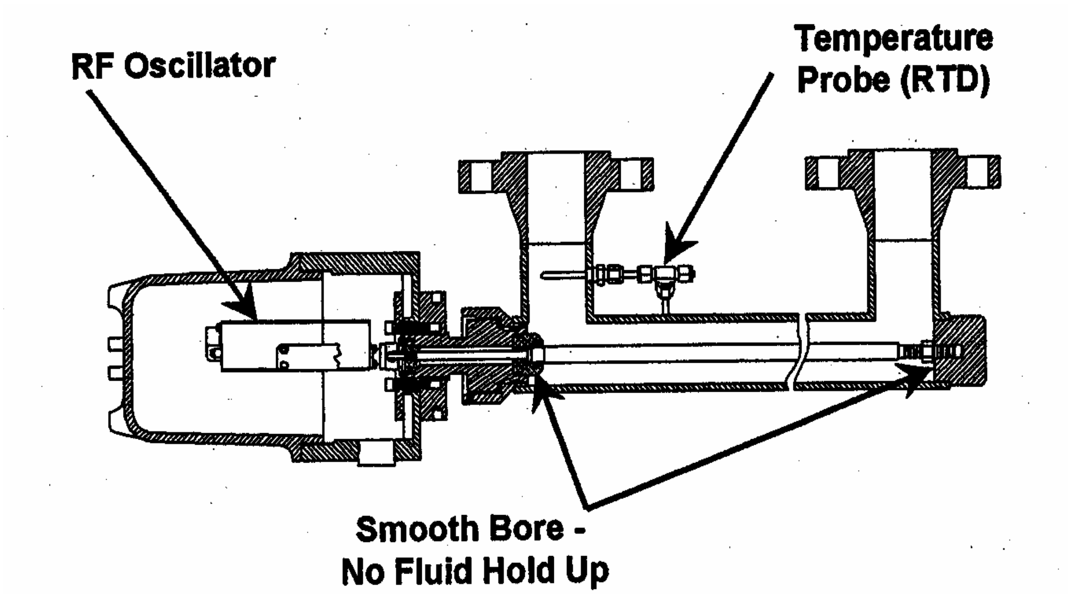

Fig. 3.6A - Measurement Section (Internal View) [15]

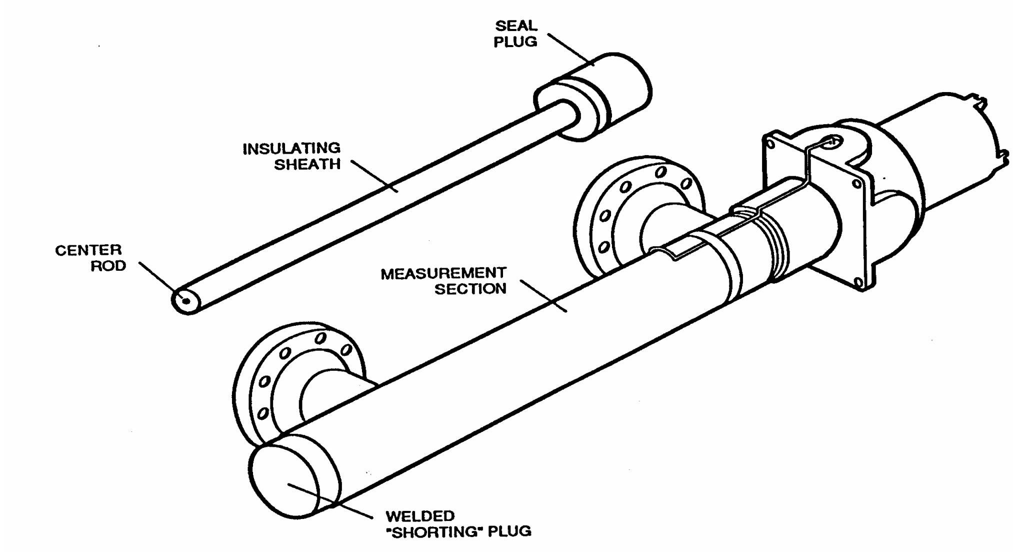

Fig. 3.6B - Measurement Section (Outer View) [15]

A standard RF connector connects the measurement section and the microwave oscillator. Two brackets hold the oscillator in order to prevent vibration from the connection.

The main electronics contain a computer, which performs the basic functions of frequency measurement, operator interface and oscillator control, calculates water percentage, and presents the data through visual display, digital interfaces, and analog I/O[12]. In addition, as the oil-water emulsion passes through, the computer continuously measures the fluid temperature and other measurement parameters, calculates the temperature-compensated water percentage, then the control electronics provide the corrections to measurement for compensate the temperature, phase and salinity of the fluids and provide updated values of water-cut and temperature to a liquid crystal display at a rate of once per second[2].

3.3.2 Principal of Operation (Oscillator Load Pull)

The Phase Dynamics carries out its operation by utilizing microwave oscillator load pull, which is a term given to describe the frequency changes of an unbuffered oscillator when its output load varies. The permittivity of the materials in the measurement section determines the output load, circuit components and the external load impedance determine an unbuffered oscillator frequency[15].

In the measurement section, the permittivity of the mixture emulsion provides a complex load which acts directly upon the unbuffered oscillator to force a predictable, repeatable, and precise change in frequency, and this frequency is proportional to the water content of the emulsion. The permittivity of the emulsion is comprised of two parts – the dielectric constant and the loss. As water percentage in the total liquid fluid change, the permittivity of the emulsion will change. Temperature and loss also affect the frequency: both are used to derive a compensation to calculate the correct water content.

On the end of the measurement section, the electronics send an electrical signal down through the fluids which generate a standing wave and this standing wave changes position as the water content changes. Then the microwave oscillator send out the signal automatically detects the change in position and changes its basic frequency depending upon how much water is in the section. The sending and the receiving portion of the electronics are the same and they change the frequency for water content. **Fig. 3.7** shows the typical measurement operation of the Phase Dynamics water-cut meter.

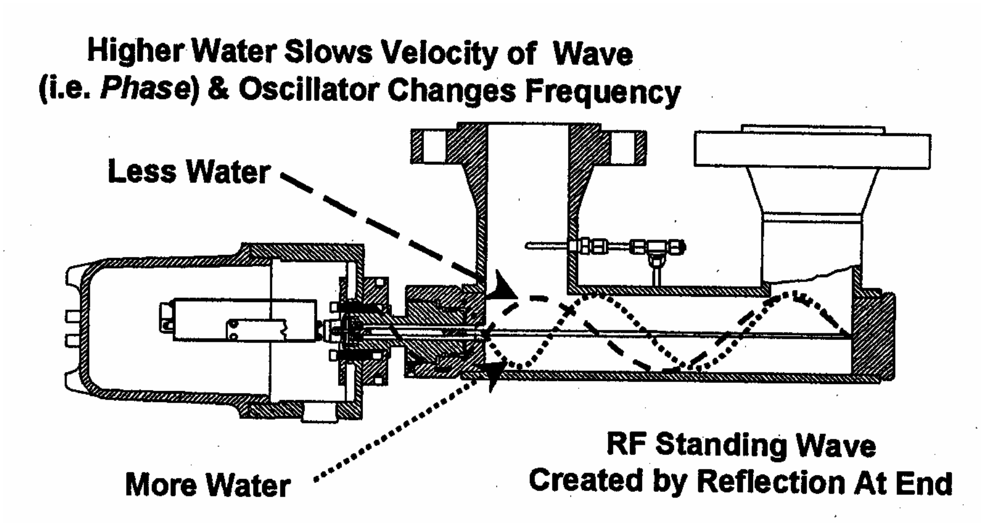

Fig. 3.7- Typical Measurement Operation of the Phase Dynamics Water-Cut Meter[15]

3.3.3 Typical Operation

The oscillator module contains two separate oscillators: the oil oscillator and the water oscillator. Each one is designed for optimum frequency pulling when changing water-cut. In oil-continuous water-cuts, the oil oscillator is about 100 MHz of frequency and provides 200 KHz frequency change for one percent change. Under water-continuous condition, the water oscillator is about 130 MHz of frequency and provides 50-150 KHz for one percent change, depending on the water salinity value[12]. Since reflected power level is representative of the RF loss of the fluids, the system will select the correct oscillator. When reflected power levels are higher, the emulsion is oil-continuous, reflected power levels are lower, the emulsion is water-continuous [5].

In operation, the reflected power levels of the oscillator are measured by the system, and then the system compares this measured value to a predetermined threshold. As the measured power level above the threshold, the system will switch to the oil-phase oscillator, measure the frequency change and calculate water-cut. Similarly, for below the threshold, the emulsion is water-continuous phase, the system will switch to the water-phase oscillator, measure the frequency change and calculate water-cut, finally system will recheck the power level in order to confirm the water continuous phase state. **Fig. 3.8** shows the water continuous phase typically starts about 65% water cut[5].

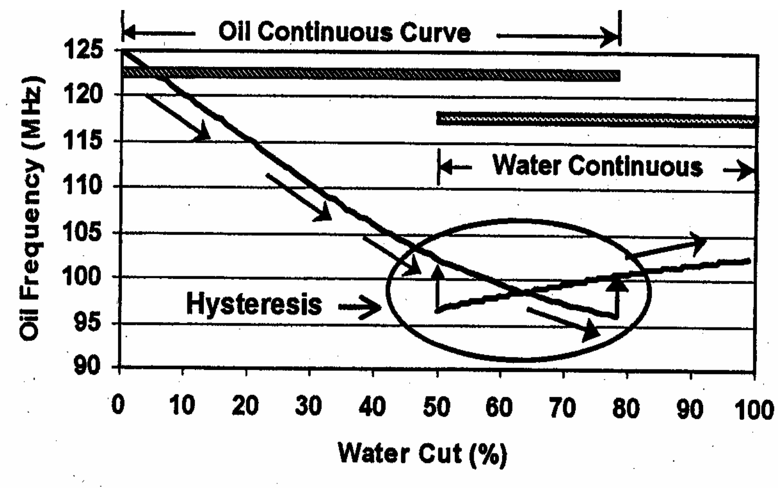

Fig. 3.8 - Emulsion Phase Behavior[15]

Under normal conditions, the analyzer's operating sequence may be described by the following chain of events:

The fluids flowing through the measurement section act on the unbuffered microwave oscillator to force a change in its natural frequency of oscillation. The temperature sensor which is inserted directly into the liquid stream will detect the temperature of fluid through the pipe near the microwave oscillator.

The oscillator's reflected power signals are measured. This information is used to determine the emulsion phase: water- in-oil phase or oil-in-water phase.

The frequency, temperature, and reflected power signals are transmitted via the system cable from the oscillator module to the electronics unit. The frequency measurement cycle is repeated approximately once per second to provide an instantaneous, continuous, and real-time measurement of water content.

3.4 Technology Gap – Entrained Gas Effect

Multiphase measurement is often performed on the surface, where pressures are relatively low. In operation there are two ways in which entrained gas may be present:

- Gas carry-under with liquid stream
- Gas evolving out of solution in the crude oil

High liquid viscosity, improper separator operation, a separator with a buildup of sand in the bottom, or poor separator design may cause gas carry-under. As pressures are reduced, gas dissolved in the oil is released which cause gas to flash out of solution when production fluid flows from the separator to the meter. The amount of evolved gas depends on oil properties, operating temperature and pressure, and pressure drop. Both of these effects increase the volume of gas present at multiphase meter and will affect the meter measurement accuracy.

The dielectric constants of the water (68 to 80) and oil (2.5) are very different, when gas (1) entrains, it will decrease the dielectric constant of the emulsion in the measurement section. Thus the presence of gas tends to increase the percentage of oil in the measurement stream. **Table 3.2** shows the effects of gas for various water cuts from test run by Shell and presented by Phase Dynamics Inc[12]. These results indicate when gas is entrained, the Phase Dynamics water-cut analyzer reading will be reduced. At higher water-cuts, the error is seen to increase.

Table 3.2- Effect of Free Gas on Water-Cut Measurement

Actual Water %	Gas Volume Percent %	Phase Dynamics Measured Water	Error %
20%	2%	19.8%	0.2%
20%	5%	19.5%	0.5%
20%	10%	19.0%	1.0%
20%	20%	18.0%	2.0%
50%	2%	49.5%	0.5%
50%	5%	49.0%	1.0%
50%	10%	48.0%	2.0%
50%	20%	47.0%	3.0%
90%	2%	88%	2%
90%	5%	85%	5%
90%	10%	80%	10%
90%	20%	70%	20%

CHAPTER IV
TEST FACILITY AND PROCEDURES

4.1 Flow Loop

Preliminary experiments were conducted in the Texas A&M Tommie E. Lohman Fluid Measurement Laboratory at pressure less than 50 psig (0.45 MPa). Compressed air is delivered to the laboratory at a pressure of 80 psig (0.65 MPa) achieving a maximum flow rate of 86,219 scf/day (2,440 m^3/day). The pump for the oil achieves a maximum flow rate of 1,000 lb/min, and the pump for the water a maximum flow rate of 800 lb/min[18].

Water and oil are pumped from their respective storage tanks by the use of two sets of magnetic centrifugal pumps operated in parallel with variable-frequency drives (**Fig. 4.1**). The multiphase flow loop comprises oil, water and gas legs commingled into a single pipe just upstream the test device. The 5.08-cm-diameter multiphase loop has an equivalent length of approximately 18 m with an ANSI 150# rating. The water leg connects to the oil leg at a "y" and at about 40 cm from this junction the gas leg connects with the loop. Check valves were placed on each leg to prevent backflow. The test device is the Phase Dynamics water-cut analyzer based on the microwave principle as discussed previously. Immediately downstream of the test device is a Weed Instruments temperature sensor model RTD 201. About 1.8 m from the water-cut analyzer, a 9 m hose connects the loop to the suction of the settling tank, which is 1.2 m in diameter and 1.37 m in height with a capacity of 1.7 m[17].

In order to ensure well-mixed flow, a static mixer is located immediately upstream of the Phase Dynamics meter. The mixer is utilized in these tests (see **Fig. 4.2**) to make sure the multi-phase flow regime is a homogeneous flow before entering the water-cut analyzer (**Fig. 4.3**).

After separation, the oil is pumped back from the settling tank to its storage tank with a progressing-cavity-pump storage. The air is vented to the atmosphere. The operating conditions of the flow loop are monitored by using temperature probes and pressure transducers. **Table 4.1** lists the equipment used in the experiment.

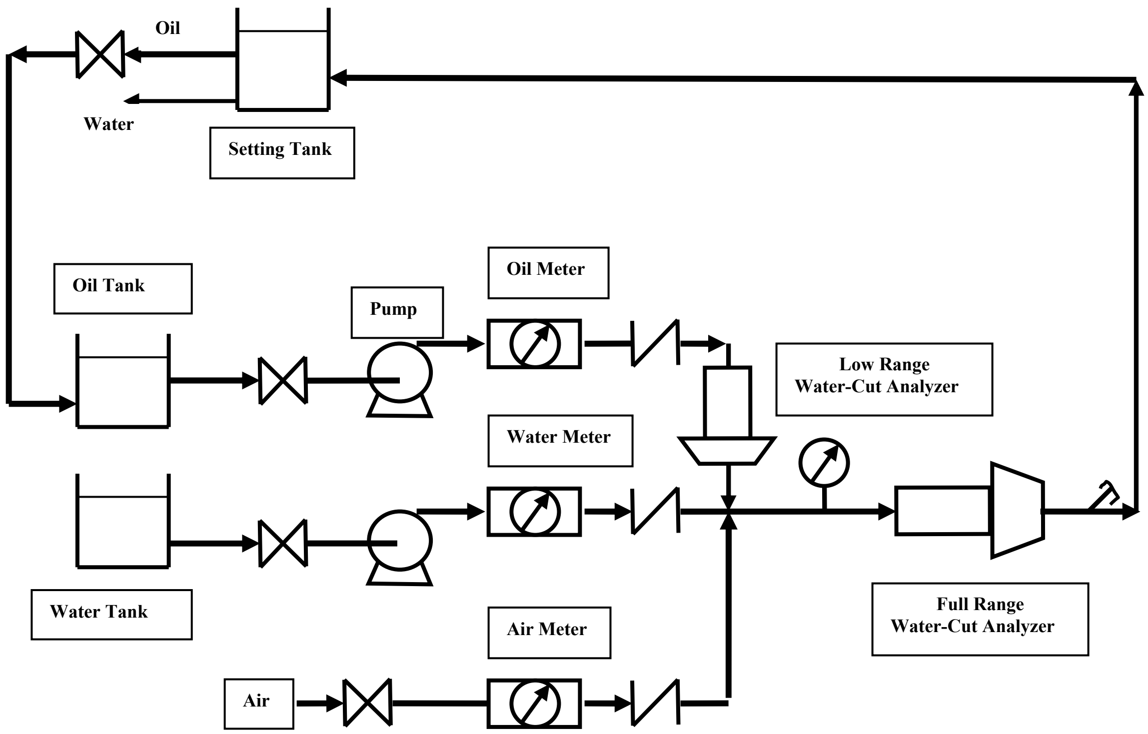

Fig 4.1- A Schematic of the Process

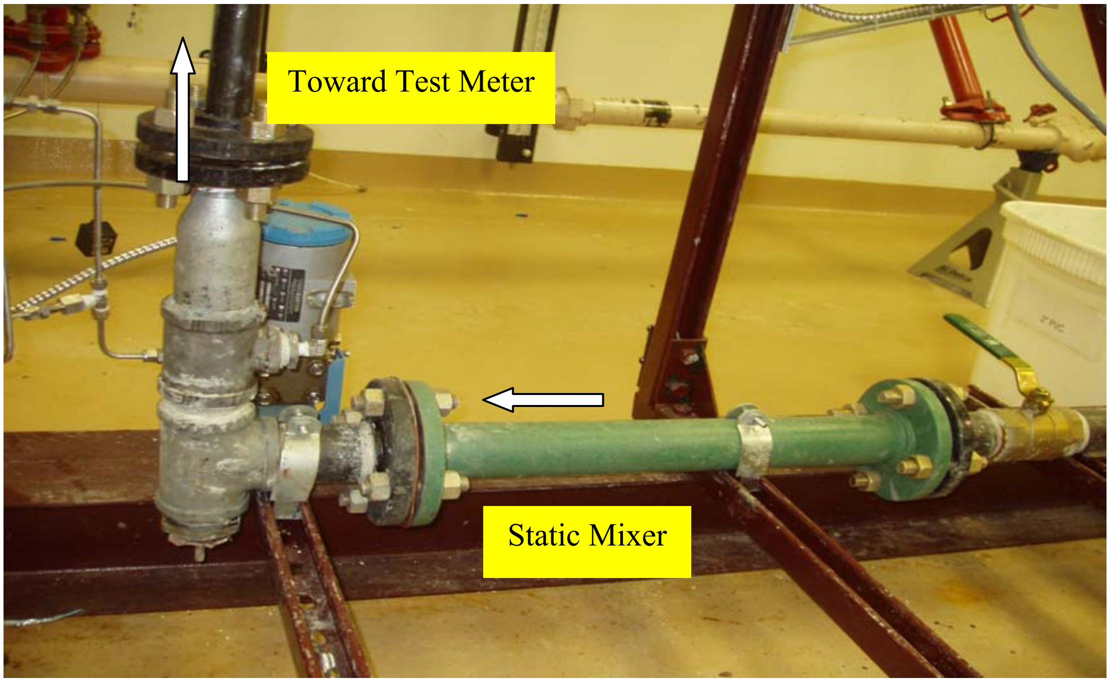

Fig 4.2- Installation of Static Mixer

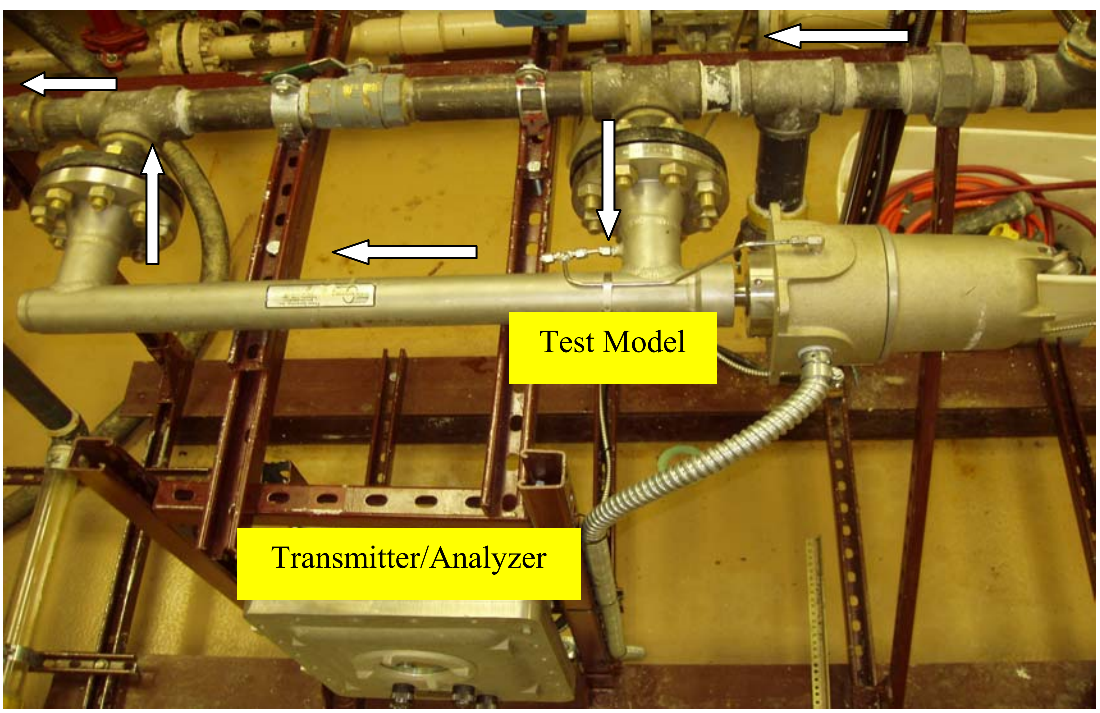

Fig 4.3- Detailed Installation of Water-Cut Analyzer

Table 4.1- List of Equipment Used

Equipment	Details/ Model	Size	Volume	Rates	Horse power
Settling Tank	White plastic w/cover	4ft x 4.5ft	450 gal		
Micro Motion Coriolis Meter	D150S/RFT 9739	1 1/2-inch		0-1400 lb/min	
Micro Motion Coriolis Meter	D150S/RFT 9739	1 1/2-inch		0-1400 lb/min	
Micro Motion Coriolis Meter (elite series)	CMF010/RFT 9739	1/4-inch		0-0.3 lb/min	
PhaseDynamics Water-cut Analyzer	S/N 1239	2-inch		full range (0-100%)	
PhaseDynamics Water-Cut Analyzer	S/N	2-inch		Low range (0-10%)	
Water Centrifugal Pump (2 sets in parallel)	Magnetic Coupling w/ VFD			5 gpm@ 34 psig; 60 gpm@ 26 psig	2
Oil Centrifugal Pump (2 sets in parallel)	Magnetic Coupling w/ VFD			5 gpm@ 46 psig; 115 gpm@ 35 psig	5
Progressing Cavity (PCP)	Reliance Electric w/ VFD				2
Oil Storage Tank (Green Fiberglass)	on platform w/ cover (tapers at the top)	39-inch x 5ft	250 gal		
Oil Containment Tank (White Plastic)	w/cover	4ft x 4.5ft	450 gal		
Water Storage Tank (White Plastic)	w/cover	4ft x 4.5ft	450 gal		
Barton Pressure Transducer	FHGG-1018T			0-100 psig	
Weed Instruments Temperature Sensor	RTD 201	(0.125 x2.5)in.		0-500°F	

4.2 Test Section

The flow measurements recorded for verification of the test device consisted of flow rate and density of oil, flow rate and density of water, flow rate and temperature of air, pressure and temperature of the pipeline. Reference measurements of both oil and water were performed with a 1 ½ (38mm) Micro Motion coriolis mass flow meter (DS150) with an accuracy for liquids of ± 0.2% of rate and a flow range of 0 to 1400 lb/min, while that of air was metered using a ¼ (2.5mm) Micro Motion coriolis mass flow meter (CMF010) with an accuracy for gas of 0.5% of rate and a maximum flow rate of 0.3 lb/min.

Measurement of water-cut is made with a 2 inch full range (0-100%) Phase Dynamics microwave water-cut analyzer which records the water-cut with an accuracy of ± 0.5% for oil phase and ± 1% for water phase[2,12]. Another 2-inch low range (0-10%) Phase Dynamics microwave water-cut analyzer which has an accuracy of ± 0.1% was connected to the oil leg to monitor the separation process.

4.3 Instrumentation and Data Acquisition System

The 4 to 20 mA outputs of the pressure transducers, temperature sensor, the transmitters of the Micro Motion coriolis mass flow meters and water-cut signal from Phase Dynamics water-cut analyzer are fed to two NI 6014 boards (16-bit analog) with a sample rate of 2 scans per sec (**Fig. 4.4**). Data was acquired using a LabVIEW software package. The Operator Interface for the System Using LabVIEW Software is shown in **Fig. 4.5**.

4.4 Test Fluids and Properties

Two different kinds of oils were used for this study: light mineral oil Conoco LVT-200 and hydraulic oil Mystik ISO 46. Their physical properties are given in **Table 4.2**. The water used was treated community water with a density of 0.9984 g/cc. When these oils were tested with water in a blender, we observe the hydraulic oil to yield a more stable emulsion than the mineral oil.

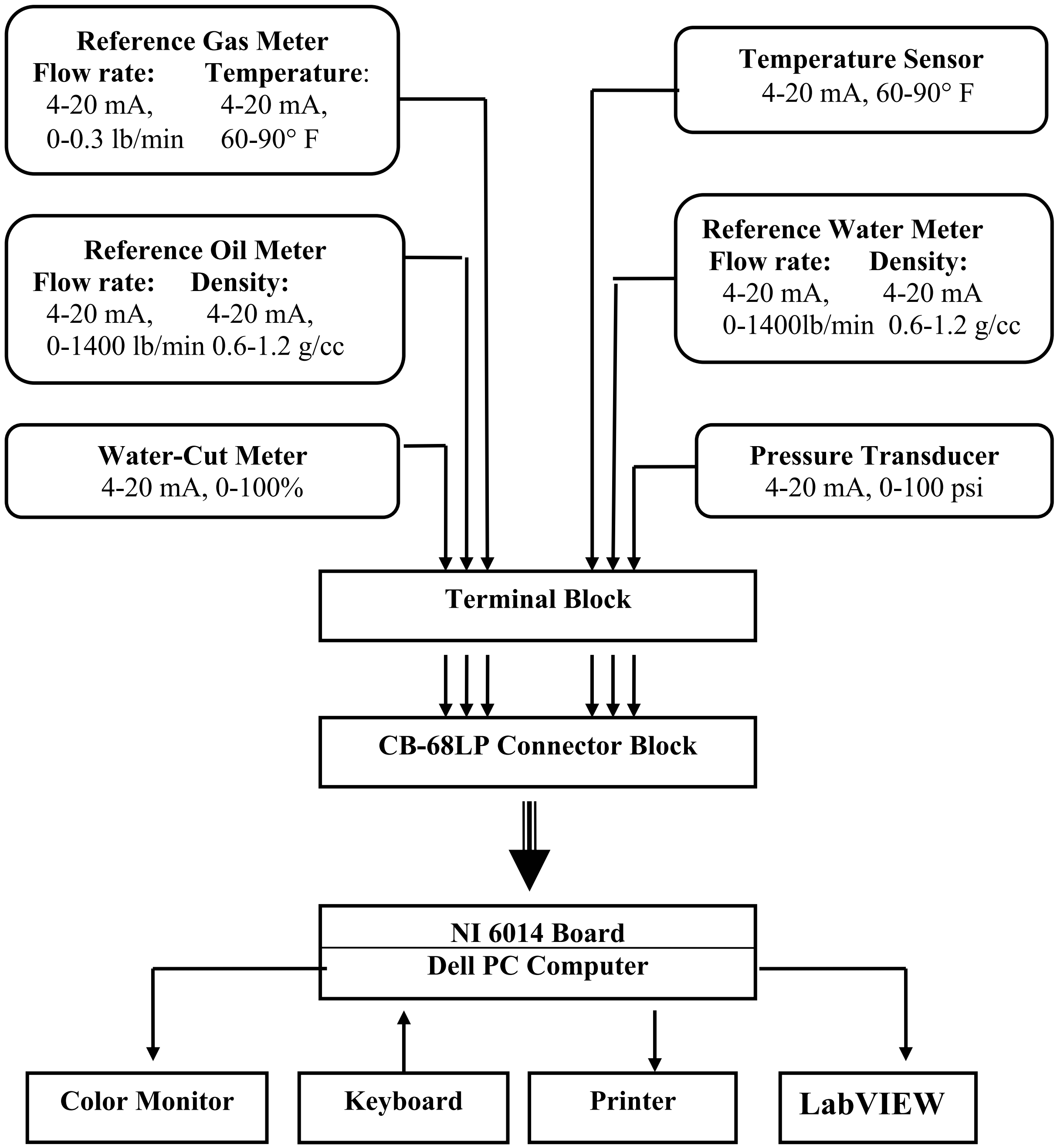

Fig. 4.4- Data Acquisition System

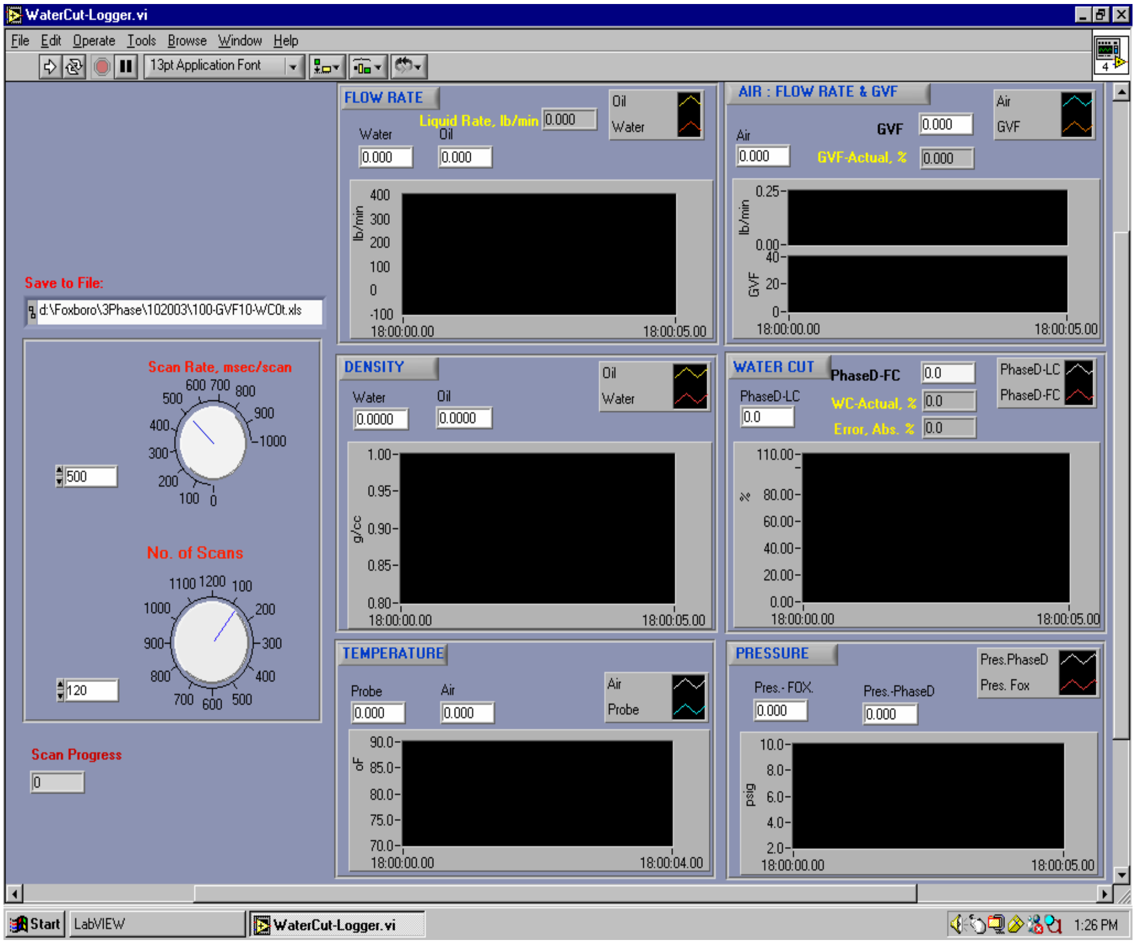

Fig. 4.5- The Operator Interface for the System Using LabVIEW Software

Table 4.2- Comparison of Properties of Oil Used in the Tests:

	Conoco LVT 200	**Mystik ISO 46**
ISO Viscosity Grade		46
Gravity, °API @60°F		30
Specific Gravity @60°F	0.86-0.88	0.87
Viscosity @40°C (cP)	2	40
Flash Point, °F	505	468

4.5 Test Procedures

The experimental procedure entailed flowing water, oil and air through the test device at varying concentrations of each component. The flow rate and pressure were allowed to stabilize for approximately 30 seconds before data acquisition was performed. Separation is achieved by the means of a settling tank. The oil phase is later pumped back to the storage tank while the air is vented. At a constant total liquid mass flow rate and GVF, monitoring and adjusting the reference oil and water flow vary the water-cut.

4.6 Test Matrix

The tests focused on the liquid-dominated, oil-continuous conditions with GVF ranging from 0 to 25% and water-cut ranging from 5 to 30%. Liquid flow rates are from 300 to 500 lb/min. The test matrix is shown in **Table 4.3**.

Table 4.3- Test Matrix

	GVF (%)																	
	300 lb/min						400 lb/min						500 lb/min					
Water-Cut(%)	0	5	10	15	20	25	0	5	10	15	20	25	0	5	10	15	20	25
5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
10	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
15	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
20	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
25	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
30	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

CHAPTER V
RESULTS AND DISCUSSIONS

5.1 Test Results and Discussions

The results and analysis for the experiments conducted in this study are presented here. Data points were obtained at total liquid flow rates of 500 lb/min, 400 lb/min and 300 lb/min based on mineral oil. A limited number of tests were conducted using the hydraulic oil (**Table 5.1**) because the high viscosity hydraulic oil was found to be more difficult to separate, forming a tighter emulsion after each test.

Table 5.1- Test Matrix for Hydraulic Oil

	GVF (%)																	
	300 lb/min						400 lb/min						500 lb/min					
Water-Cut(%)	0	5	10	15	20	25	0	5	10	15	20	25	0	5	10	15	20	25
5																		
10				X														
15																		
20					X			X										
25			X											X				
30									X						X			

It should be noted that the volume errors are reported rather than mass flow error, as volume is the preferred measure of quantity in the oil & gas industry. Both volume error and water cut were calculated using the reference meters. Here R_{act} refer to actual reading, P_{ph} refer to Phase Dynamics reading, and the other WC reading like calculated R that will be utilized in the analysis of the results.

Flow Rate. **Figs. 5.1, 5.2, and 5.3** show the ratio of 2-inch Phase Dynamics Reading (mineral oil) to actual Reading at 0 – 25% GVF under 3 different total flow rates. **Figs. 5.4, 5.5, and 5.6** show the ratio of Phase Dynamics Reading (mineral oil) to actual reading at 5 – 30% WC under 3 different total flow rates. Although minor differences can be identified in the range of errors encountered between each total liquid flow rate, we still can say the volumetric flow rate will not affect the water-cut reading when the emulsions are well mixed.

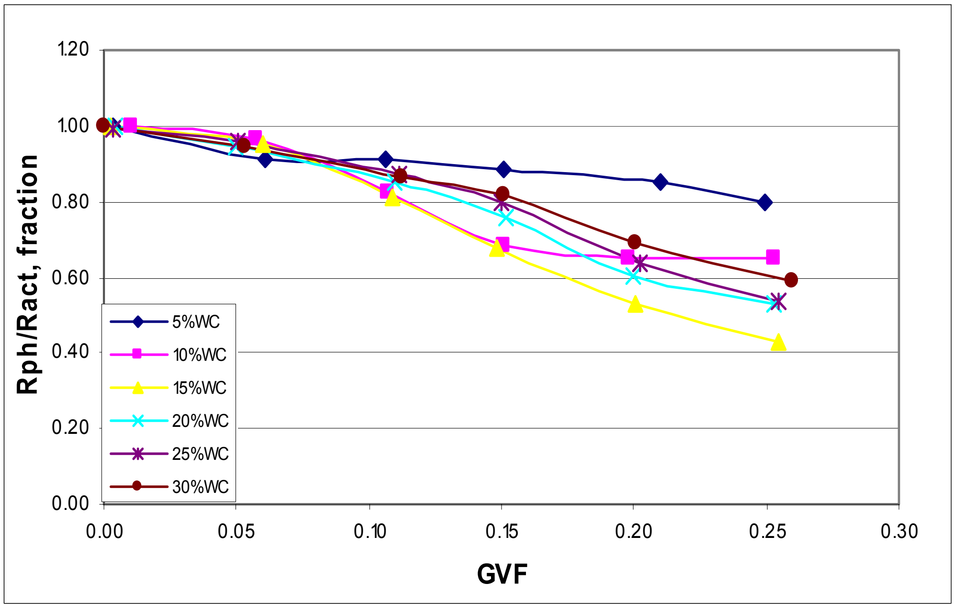

Fig. 5.1- R_{ph}/R_{act} vs. GVF at 500 lb/min

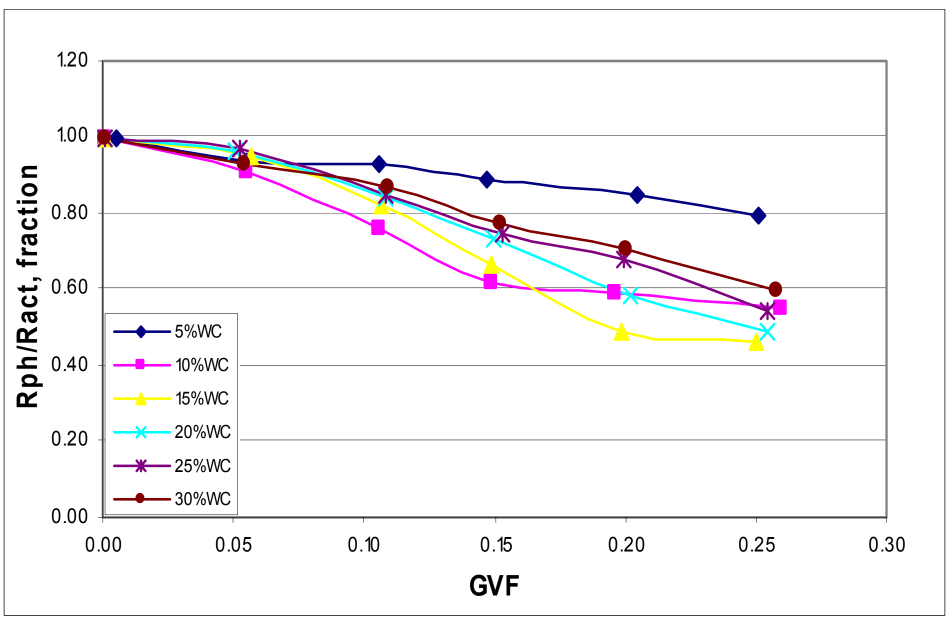

Fig. 5.2- R_{ph}/R_{act} vs. GVF at 400 lb/min

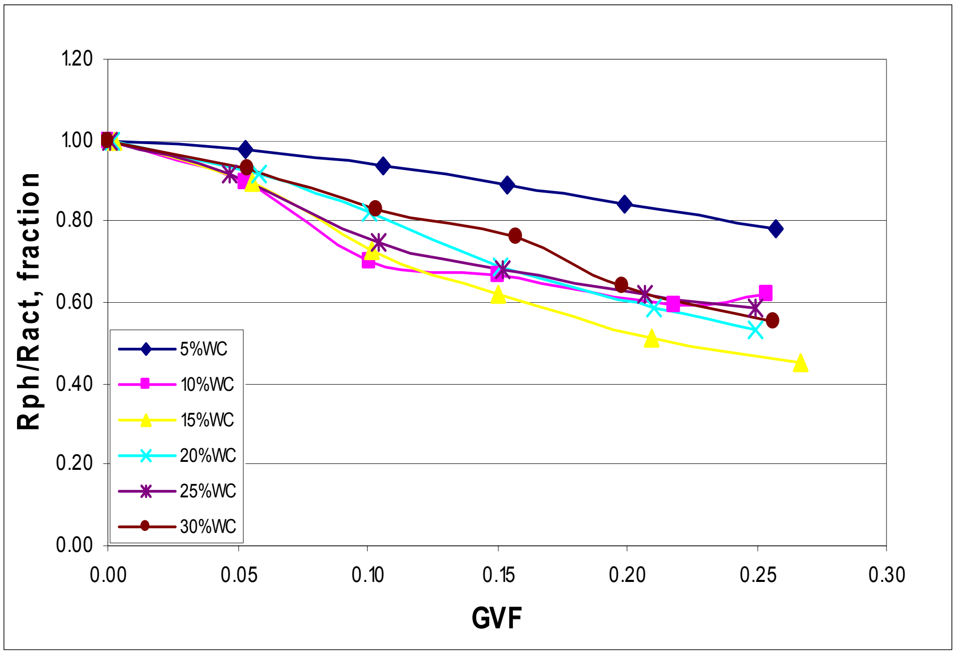

Fig. 5.3- R_{ph}/R_{act} vs. GVF at 300 lb/min

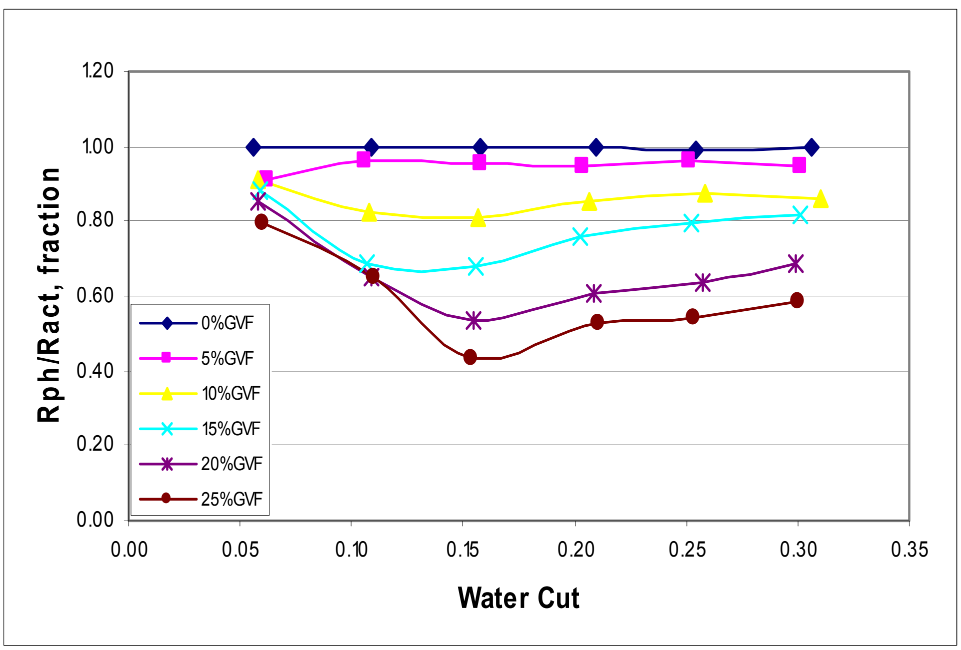

Fig. 5.4- R_{ph}/R_{act} vs. Water-Cut at 500 lb/min

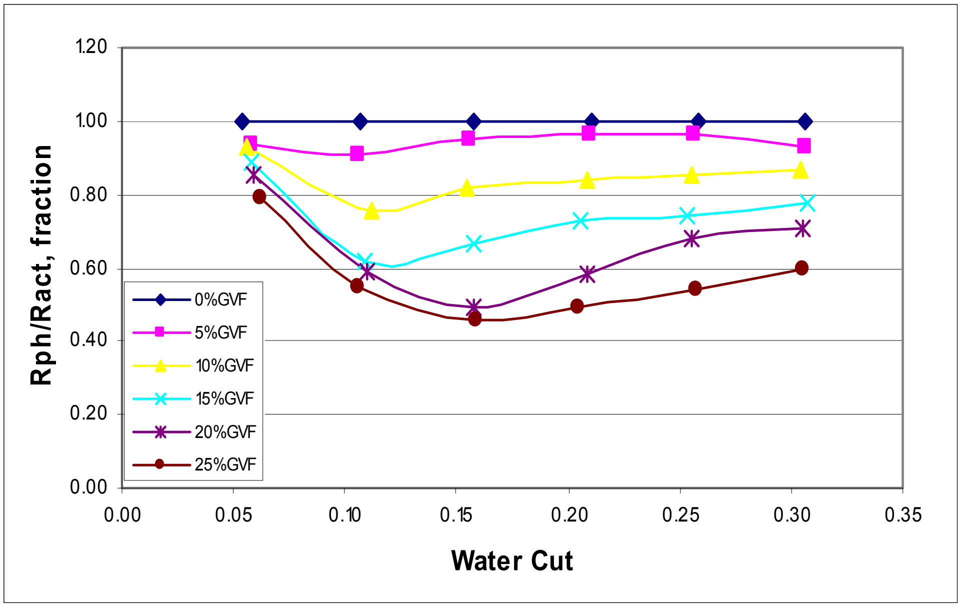

Fig. 5.5- R_{ph}/R_{act} vs. Water-Cut at 400 lb/min

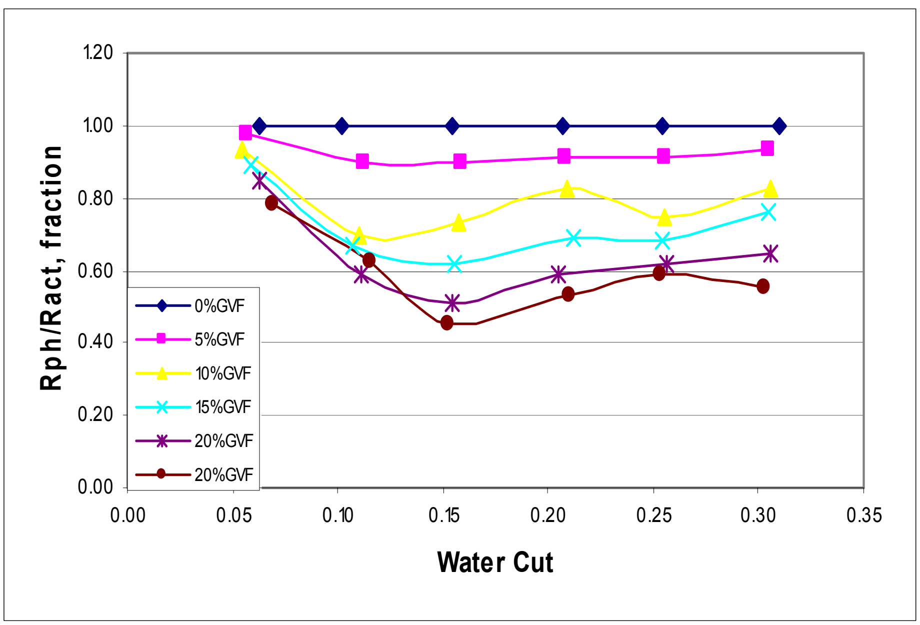

Fig. 5.6- R_{ph}/R_{act} vs. Water-Cut at 300 lb/min

GVF. **Figs. 5.7, 5.8, and 5.9** show the absolute error of water-cut taken at 5 – 30% reference water cut under 3 different total flow rates. As GVF increase, the absolute error of water-cut tended to increase. Here abs. error is expressed as following:

Abs. Error (%) = (Reading of Phase Dynamics – Real Water-cut Value)*100%

As mentioned before, entrained gas will decrease the dielectric constant of the emulsion, in addition, entrained gas also greatly affect the sizes and shapes of the dispersed droplets and produces unstable fluid flow. All of these reasons will produce water-cut reading error. Our test shows as GVF increase, the fluid flow becomes more unstable, and the error in the water-cut measurement will increase.

When GVF is at 0% this represents oil/water two-phase fluid. When the GVF is under 5%, the gas does not significant affect the water-cut reading, as the errors are less than 2%.

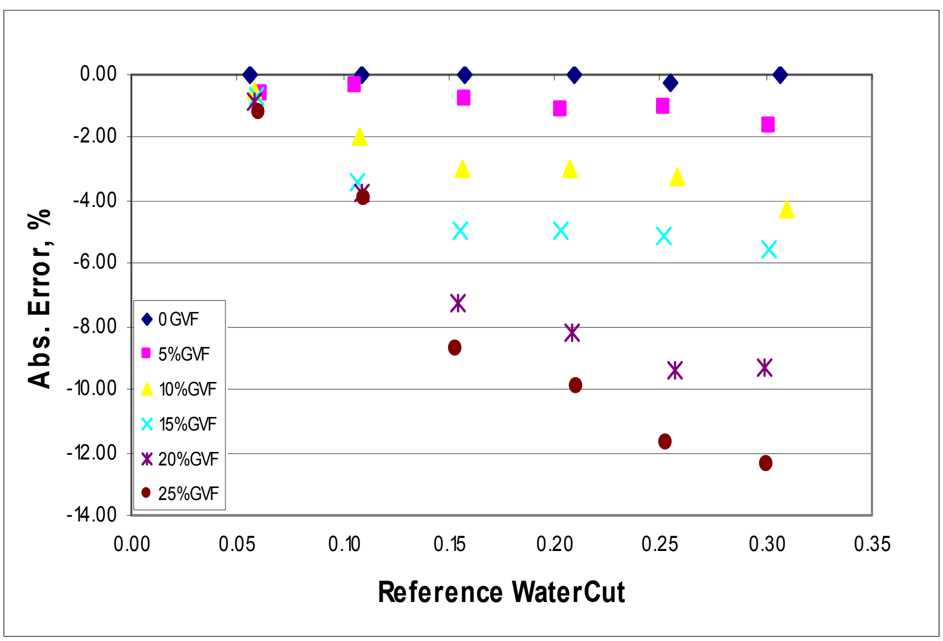

Fig. 5.7- Absolute Error vs. Actual Water-Cut at 500 lb/min

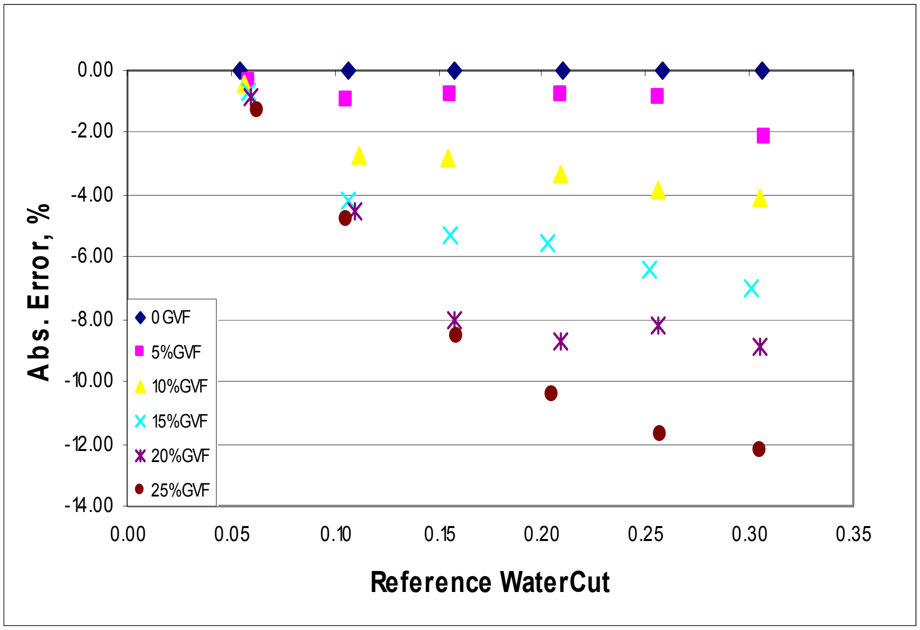

Fig. 5.8- Absolute Error vs. Actual Water-Cut at 400 lb/min

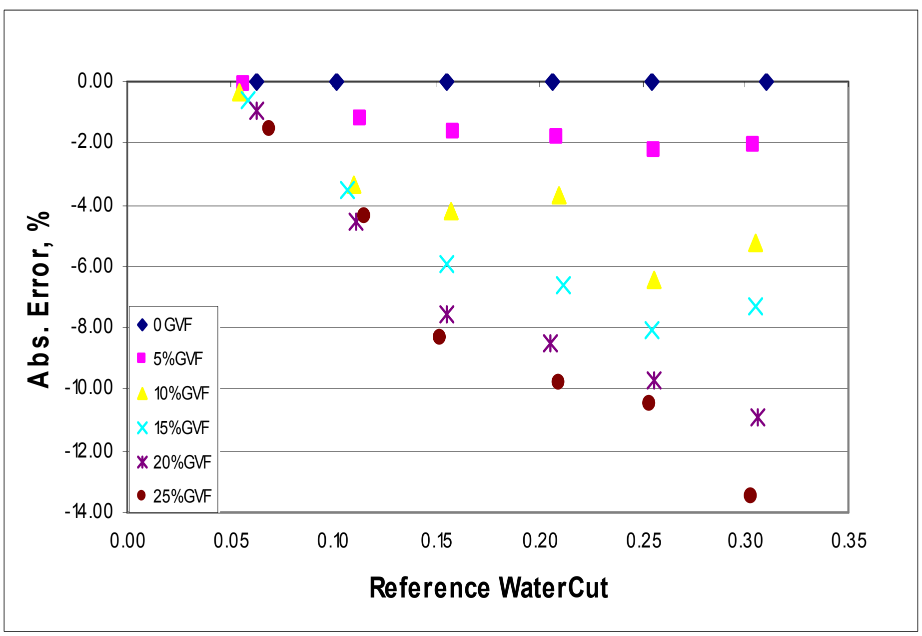

Fig. 5.9- Absolute Error vs. Actual Water-Cut at 300 lb/min

Viscosity. **Figs. 5.10, 5.11, and 5.12** show the effect of different viscosity between mineral oil and hydraulic oil under 3 different total flow rates. Although we just did some points based on hydraulic oil, test results still reveal that the absolute error of water cut dramatically decrease as the viscosity increases.

Viscosity is one of the significant effects on produced oil-field emulsion. High-viscosity oils often exhibit tighter emulsions than light oil, and the high viscosity produces smaller and stable size droplets which significant affect the property of the fluid. Different oil types produce different effect. When gas is entrained, it is harder to decrease the interfacial viscosity at a high-viscosity oil than at light oil. **Figs. 5.11, 5.12, and 5.13** show that at light oil, when more gas is entrained, they have a greater effect on the water-cut reading, while the hydraulic oil, with more gas entrained, only produces a small effect on water-cut reading.

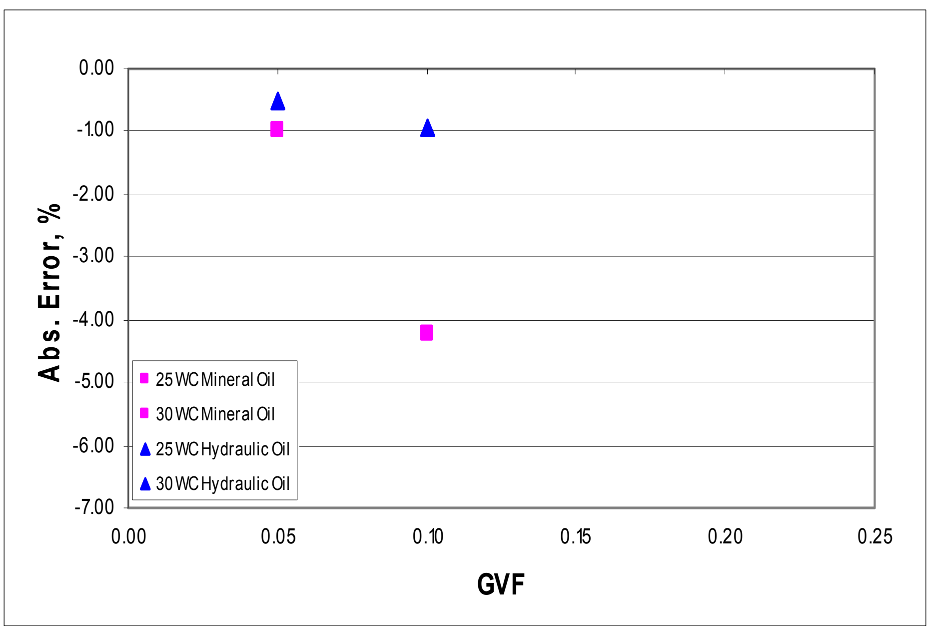

Fig. 5.10- Absolute Error vs. GVF at 500 lb/min between Mineral Oil and Hydraulic Oil

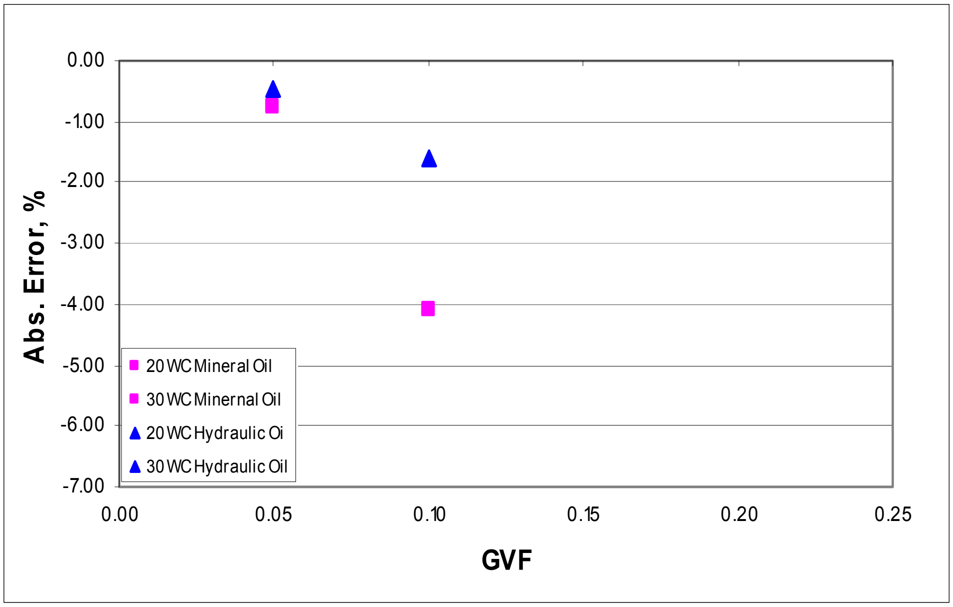

Fig. 5.11- Absolute Error vs. GVF at 400 lb/min between Mineral Oil and Hydraulic Oil

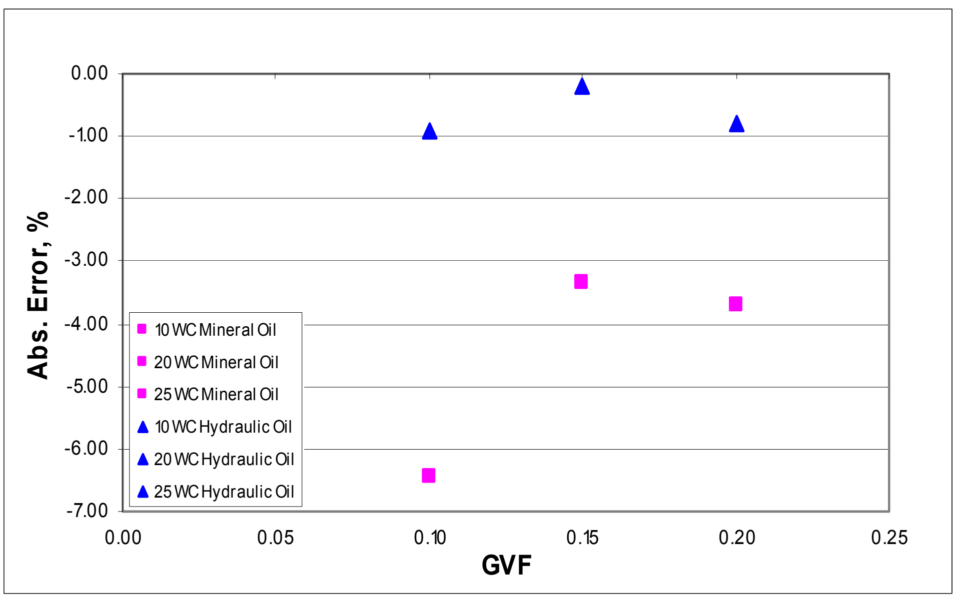

Fig. 5.12- Absolute Error vs. GVF at 300 lb/min between Mineral Oil and Hydraulic Oil

Fig. 5.13 shows the water-cut error compared with hydraulic oil, mineral oil and previously published data (from **Table 3.1**). The error data of hydraulic oil is closer to the data from Shell. Viscosity property of fluid has big effect on water-cut measurement using microwave principle.

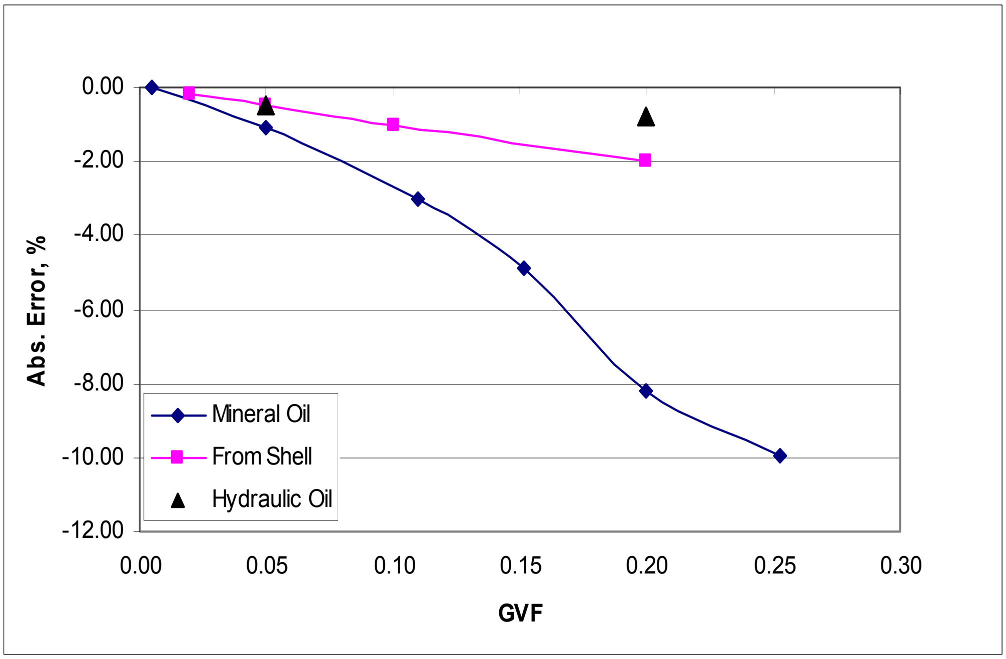

Fig. 5.13- Water-Cut Error Compared with Hydraulic Oil, Mineral Oil and Previously Published Data (Table. 3.1) under 20% Water-Cut

5.2 Comparison of Lab Data with Theoretical Model

In order to correlate the effects of the gas carry-under, the below discussion is focused on using the 500 lb/min mineral oil tests. These high rate tests were found to give a good representation of the whole data set.

First, let's see whether Phase Dynamics reading match the reading of reference meter under two-phase system. Reading for reference meter can be obtained from each single oil, water, and gas meter. **Fig. 5.14** shows water-cut reading from Phase Dynamics match reference meter under two-phase.

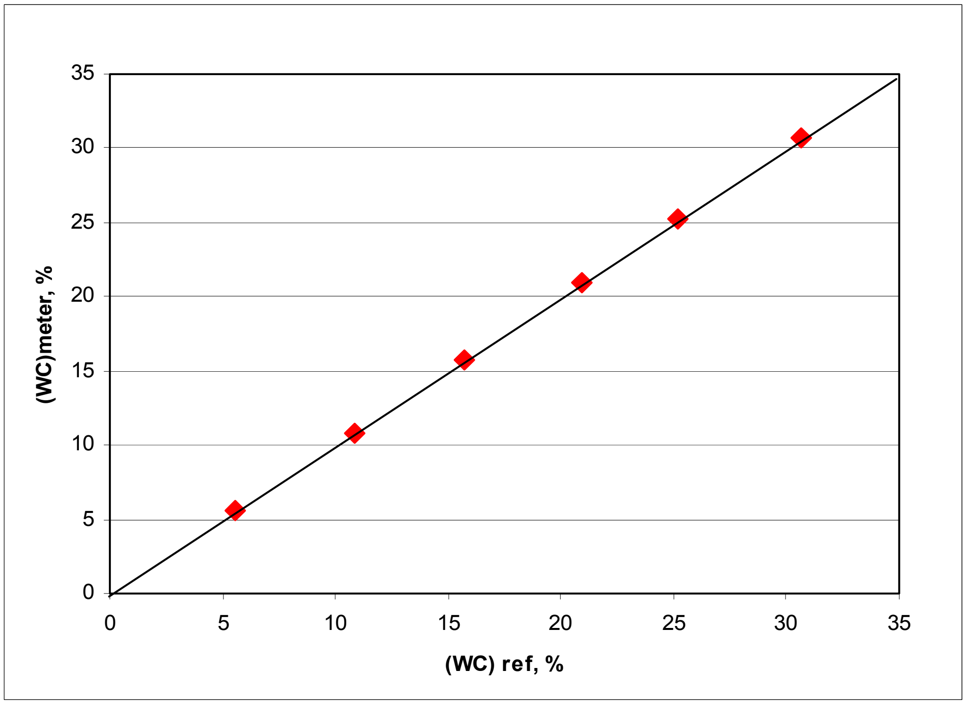

Fig. 5.14- Comparison of Water Cut Reading Between Phase Dynamics and Reference Meter

Use Wagner's equation (Eq.2.9) to calculate the ε_L, then use ε_L and water-cut of reference meter to get one regression equation with zero gas fraction only. **Fig. 5.15** shows the regression results and have a regression equation below (Eq. 5.1).

$$WC = -1.173\varepsilon_L^2 + 19.699\varepsilon_L - 41.465 \quad (5.1)$$

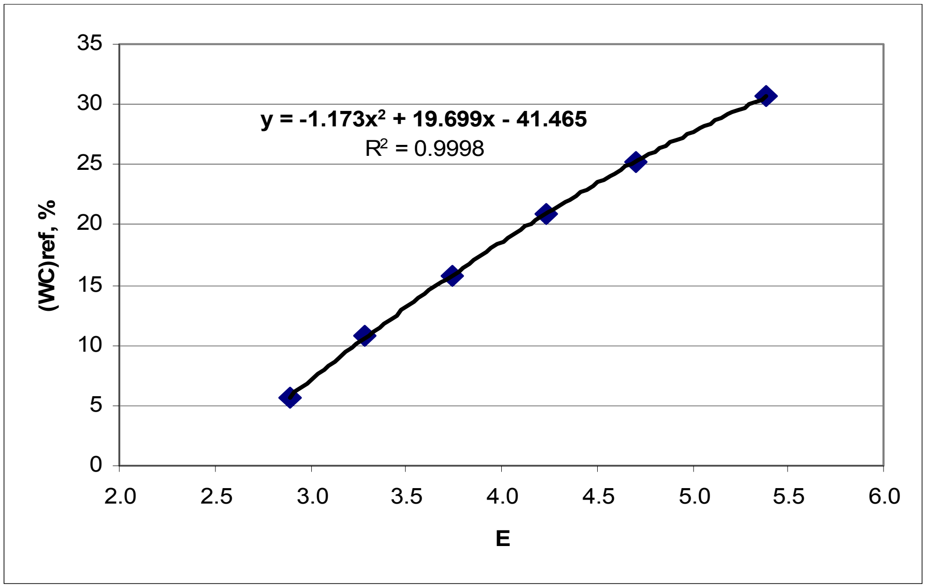

Fig. 5.15-Regression Equation Using ε_L and Water-Cut of Reference Meter

Fig. 5.16 shows water-cut results using the regression equation and compare with the reading of Phase Dynamics meter, it is pretty match.

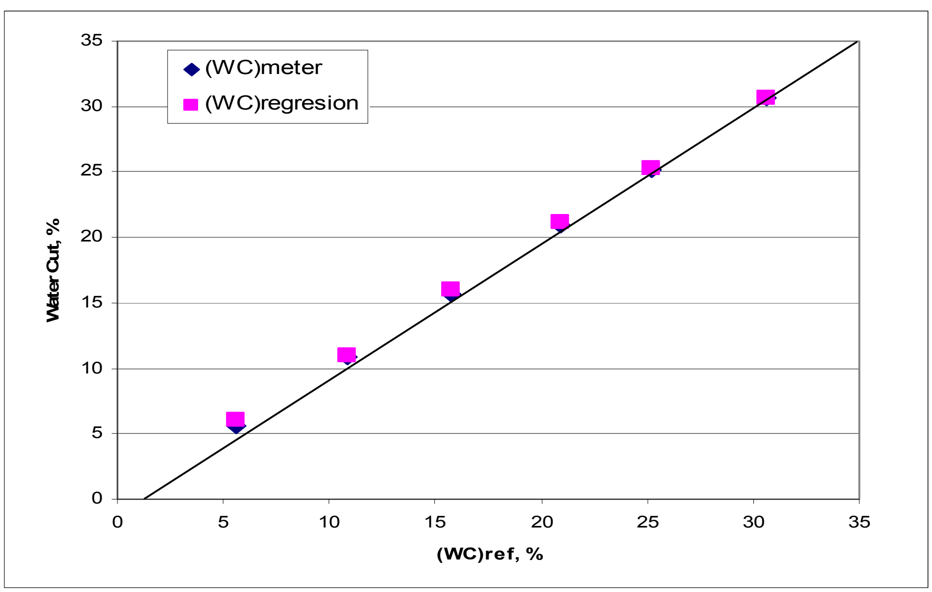

Fig. 5.16- Comparison Results of Water-Cut between Regression Equation and Phase Dynamics Reading

5.3 Correction of Phase Dynamics Analyzer's Data for the GVF

Knowing the reading of the Phase Dynamics meter under three-phase system and GVF of the system, a mathematical model can be created to correct the two-phase measurement. The mathematical equation shows below (Eq. 5.2) was obtained by correlating the mineral oil data taken in this study.

$$WC_{\Pr edicted} = -0.006WC_{Ph}^{2} + 1.2978WC_{Ph} + 0.29996GVF - 3.239 \ldots\ldots(5.2)$$

The term WC_{Ph} is the reading from the Phase Dynamics meter and $WC_{Predicted}$ is the water-cut value corrected for the presence of gas, indicated by the GVF.

Fig. 5.17 shows the predicted water cut of Phase Dynamics analyzer with reference water cut. The predicted values very closely match the values from the reference meter.

Fig. 5.18 also shows the error produced by Phase Dynamics analyzer's predicted water cut. The maximum of error across a wide range of GVF's is about ± 2.3% for predicted water cut.

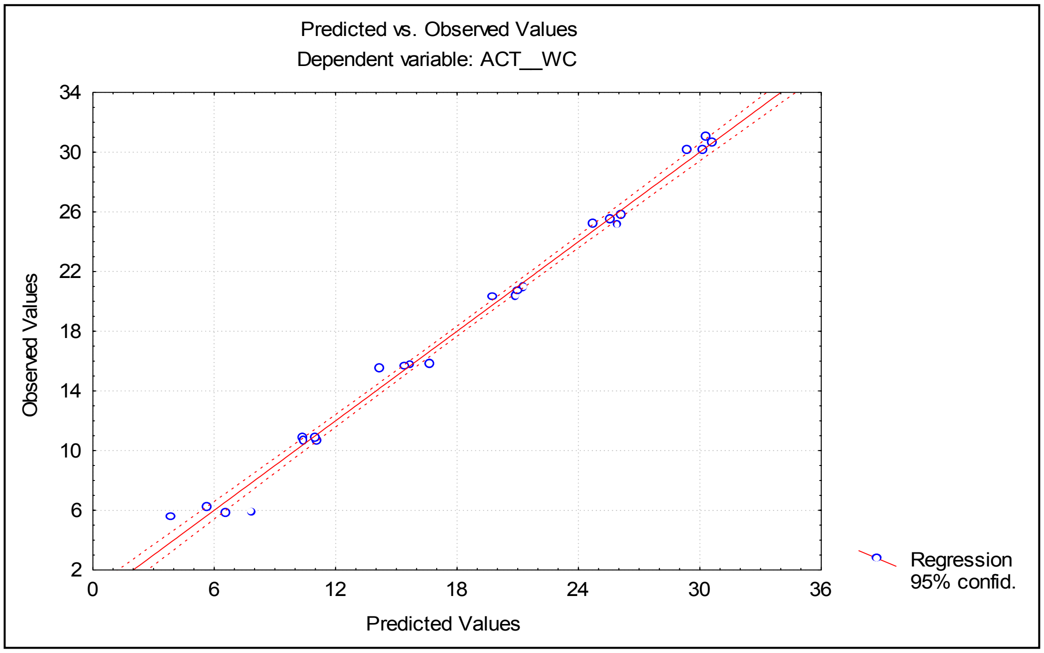

Fig. 5.17-Predicted Water Cut of Phase Dynamics Analyzer with Reference Water Cut

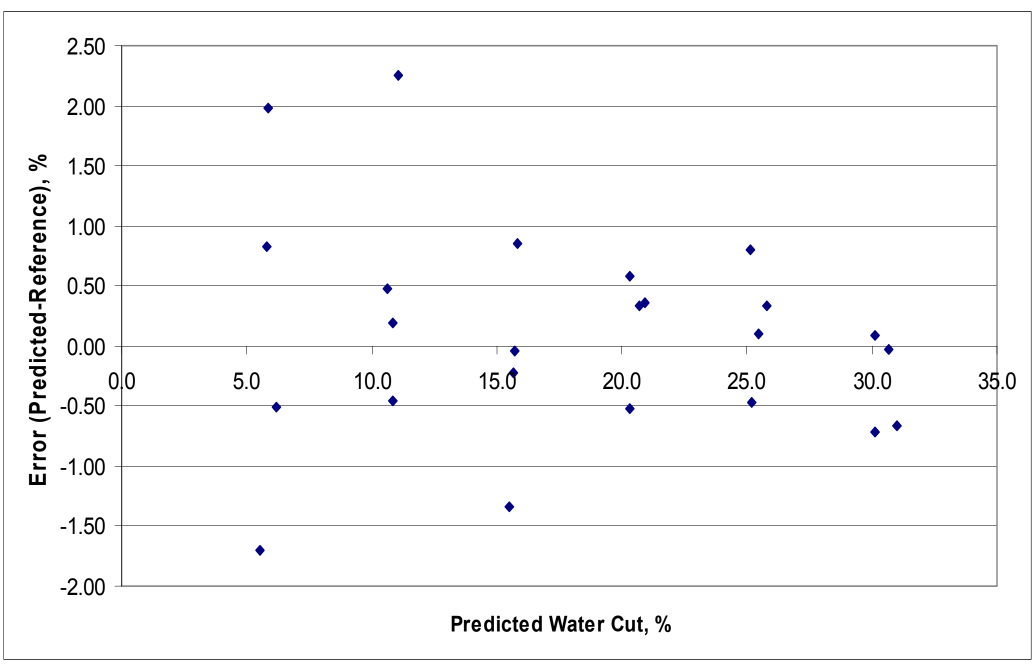

Fig. 5.18-Error Produced by Phase Dynamics Analyzer's Predicted Water-Cut

CHAPTER VI
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the theoretical and experimental investigations, the following conclusions can be drawn:

1. ***Effect of GVF***. Entrained gas was found to decrease the dielectric constant of the emulsion. The more entrained gas, the less dielectric constant of the emulsion, which yields lower water-cut. GVF increases, the error in the water cut reading increases, and the error is very close to the results obtained using a theoretical model when GVF less than 5%. That is, when GVF is less than 5%, the gas will not affect the water-cut reading.

2. ***Effect of Viscosity***. Although the viscosity effects are not included in the Wagner's equation, the high-viscosity oil appears to result in more uniform shapes and consistent in the dispersed small oil droplets. Therefore these droplets of hydraulic oil have an even greater resistance to settling. Emulsion size and shapes significant affect the characteristic of dielectric constant. So while high viscosity tends to increase gas carry-under in a separator, the higher viscosity results in a droplet distribution that is less sensitive to gas effects.

3. ***Effect of Volume Flow Rate.*** Through the test it was observed that the volumetric flow rate will not affect the water-cut reading when the emulsions are well mixed.

4. ***Theory Model.*** Theoretical models like Wagner's equation for two-phase system pretty match the results of experiments. And the same time, a non-linear model was proposed and compared to lab data which corrects Phase Dynamics analyzer's data for the GVF.

6.2 Recommendations

In this test, data was acquired use a LabVIEW software package, while control of the flow rate of oil, water and gas maintain manual, in order to better control the pump speed , the future work is to build the control process from the computer to allow easier loading of the loop.

Through the discussion above, we found the high-viscosity oil has better result than low-viscosity oil, we only got data at some points for hydraulic oil because hydraulic oil is more difficult to separate, and easier to form tighter emulsion once having black iron or galvanized steel fittings, the rust will make emulsion more stable. Maybe in the future we should try to add more things include surfactants, anti-oxidents, and other special chemicals to improve the performance and extend the life of the oil.

NOMENCLATURE

R_{act}	Actual reading
ε_C	Continuous phase dielectric constant
ρ_g	Density of gas
ρ_o	Density of oil
ρ_w	Density of water
ε_D	Dispersed phase dielectric constant
z	Distance traveled through a homogeneous absorbing medium
P_p	Dynamic pressure loss in flow line and fittings from the test separator to the flow meter inlet
f_g	Gas volume fraction
I_i	Initial intensity
d	Inside diameter of the pipe
I	Intensity
P_s	Liquid static head measured from the liquid level in the separator to the flow meter
μ	Mass absorption coefficient
μ_g	Mass absorption coefficient of gas phase
μ_o	Mass absorption coefficient of oil phase
μ_w	Mass absorption coefficient of water phase
ε_o	Oil phase dielectric constant
f_o	Oil volume fraction
R_{ph}	Phase Dynamics reading
P_m	Pressure drop across the flow meter
ε_L	Two phase mixture dielectric constant
ε_w	Water phase dielectric constant

f_w Water volume fraction

WC Water-Cut

$WC_{Predicted}$ Water-Cut of Phase Dynamics predicted values

WC_{PD} Water-Cut of Phase Dynamics reading

WC_D Water-Cut under dispersed phase

WC_W Water-Cut under water-continuous phase

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