Multiphase Flow Metering Technique Based on Passive Fiber Optic Components for Oil Producing Wells

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Abstract: - Monitoring oil fields reservoirs for optimizing the production have been satisfied by wellhead sampling and test separator metering. Development and research work have been taking place to develop smaller size and lower cost multiphase flow meters that improve well testing and replace the large and expensive test separators. Recently some commercial multiphase flow meters were introduced that measure gas, oil and water volume flow rates at line conditions via a variety of sensing techniques. This paper is introducing with mathematical modeling, a new technique for multiphase flow metering based on passive fiber optic components "Fiber Bragg Gratings Technology". The new multiphase flow metering technique may offer higher accuracy, smaller size, lower cost, and improved corrosion and erosion tolerances, adaptive to changes in liquid density, higher safety in harsh process service.

Key-Words: - Multiphase Flow Meter, Optical Flow Sensor, Optical Sensors, Fiber Optic Sensors, Fiber Bragg Gratings, Oil Well Multiphase Metering, Oil Well Test Separator, Multiphase Liquid Level, Fiber Bragg Grating Flow Sensor.

1 Introduction

To replace the traditional test separator flow metering techniques, some modern alternative multiphase flow metering technologies were introduced. Such as; 1) Phase fraction and velocity measurement based on identifying the fractions of oil, water, gas and measuring the phase velocities, either by impedance sensors or γ-ray absorption. 2) Tracers, the multiphase flow is measured by injecting fluorescent dyes that mix with the individual phases, by analyzing a sample of the multiphase fluid and combining this with the injection rate, the individual flows can be detected. 3) Pattern recognition based on multiple electronic sensors and the use of artificial intelligence to process the signals and determine the oil, water and gas flow rates [5]. However the problems involved in using these techniques can be classified as follows; 1) lower accuracy of measurement. 2) May not be suitable for all offshore installations. 3) High running cost calibration, maintenance and consumable materials. 4) None of these techniques reported to be dominant or universal solution [5]. Therefore the main objective of this paper is to introduce by mathematical modeling a new technique for multiphase flow metering based on passive fiber optic components "Fiber Bragg Gratings Technology". The proposed technique may offer higher accuracy, smaller size, lower cost, corrosion and erosion tolerances, adaptive to changes in liquid density, and higher safety in harsh process service. This is achieved, the paper sections are classified as follows: 1) Fiber Bragg gratings sensors theory and characteristics. 2) The new multiphase flow metering technique principle of operation and mathematical modeling. 3) Conclusion and discussion.

2 FBG Sensors Theory and Characteristics

Fiber optic sensor technology has been in a rapid development and displacing traditional sensors for many application such as rotation, acceleration, electric and magnetic field measurement, temperature, pressure, vibration , linear and angular position, strain, chemical measurements and a host of other sensor applications. The main advantages of fiber optic sensors are their ability to be light weight, of very small size, passive, low power, immunity to electromagnetic interference, flexibility, high temperature tolerance, high sensitivity, wide bandwidth and environmental ruggedness. The major advantage of a fiber bragg gratings sensor is that the measurand information is wavelength-encoded (an absolute quantity), thereby making the sensor self-referencing and independent of fluctuating light levels and the system immune to source power and connector losses that plague many other type of optical sensors [2, 4]. Fiber Bragg gratings are made by laterally exposing the core of a single-mode fiber to a periodic pattern of intense ultraviolet light. The exposure produces a permanent increase in the refractive index of the fiber's core, creating a fixed index modulation according to the exposure pattern. This fixed index modulation is called a grating; at each periodic refraction change a small amount of light is reflected. All the reflected light signals combine coherently to one large reflection at a particular wavelength when the grating period is approximately half the input light's wavelength. This is referred to as the Bragg condition, and the wavelength at which this reflection occurs is called the Bragg wavelength [2, 3], only those wavelengths that satisfy the Bragg condition are affected and strongly back-reflected into the same core of the fiber. The grating spacing and index of refraction are sensitive to strain and temperature effects, thus in sensing applications the shift in the reflected wavelength is proportional to the applied temperature and strain [2, 3]. Those shifts in the reflected wavelength are detected and interpreted at the end of the fiber by a process indicator or controller. Compared to most other fiber-optic components, fiber Bragg gratings are simple to manufacture, they are commonly between one millimeter and 25 millimeters long of uniform or chirp modulation, however longer gratings or custom design gratings are fabricated too, in some applications it is possible to use multiple gratings structure [2]. Selection of the grating length or design is dependent on the desired rangeability and bandwidth. An illustration diagram of a uniform fiber grating sensor is shown in figure (1) and its reflection spectrum is show in figure (2).

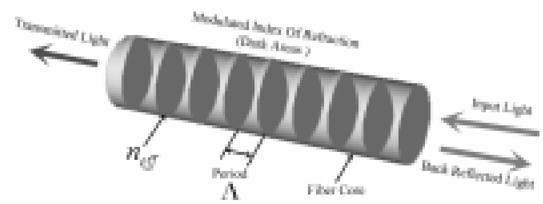

Figure (1) Uniform FBG Sensor

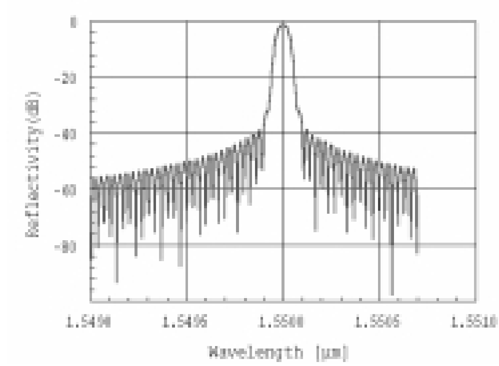

Figure (2) Reflection Spectrum of Uniform FBG Sensor

For a uniform fiber Bragg gratings sensor on a single mode fiber the relationship between the Bragg wavelengths, period, and refractive index is represented as follows [2]:

$$\lambda_B = 2\Lambda N_{eff} \qquad (1)$$

Where;

λ_B = Bragg wavelength. It is the (reflected) free space center wavelength of the input light.

n_{eff} = Effective refractive index of the fiber core at the free space center wavelength.

Λ = The grating spacing (period).

2.1 FBG temperature sensor

Equation (2) represents the mathematical model of FBG temperature sensor [1].

$$\Delta\lambda_T = \lambda_{Bo}(\alpha_\Lambda + \alpha_n)\Delta T \qquad (2)$$

Where;

λ_{Bo} = the initial or Bragg wavelength at reference temperature T_o.

$\Delta\lambda_T$ = the shift in wavelength nm, due to temperature.

$\alpha_\Lambda = \frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T}$ = The thermal expansion coefficient for the fiber $\approx 0.5x10^{-6}$

$\alpha_n = \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T}$ = The thermo-optic coefficient for the germania-doped silica-core $\approx 8.6x10^{-6}$

ΔT = The temperature change in ^OC.

For simplification equation (2) may rewritten as follows:

$$\Delta\lambda_T = \lambda_{Bo}K_T\Delta T \tag{3}$$

Where K_T is a constant value $= (\alpha_\Lambda + \alpha_n)$

The expected temperature sensitivity at a Bragg wavelength λ_{Bo} of 1550 nm, is ≈ 13.7 $pm/^oC$

2.2 FBG pressure sensor

A uniform FBG pressure sensor is represented by the following equation [2]:

$$\Delta\lambda_P = \lambda_{Bo}\left[-\frac{(1-2v)}{E} + \frac{n_{eff}^2}{2E}(1-2v)(2p_{12}+p_{11})\right]\Delta P \tag{4}$$

For simplification equation (4) may write as follows:

$$\Delta\lambda_P = \lambda_{Bo}K_P\Delta P \tag{5}$$

Where; K_P is a constant value =

$$\left[-\frac{(1-2v)}{E} + \frac{n_{eff}^2}{2E}(1-2v)(2p_{12}+p_{11})\right] \tag{6}$$

λ_{Bo} = The initial or the fabricated FBG Bragg wavelength at reference temperature of T_o and Atmospheric pressure.

$\Delta\lambda_P$ = the fractional wavelength shift in nm due to pressure.

ΔP = The applied pressure in MPa

Where p_{11} and p_{12} = the components of the strain-optic tensor (constant values)

v = The Poison's ratio, E = the fiber Young's modulus

n_{eff} = Effective refractive index of the fiber core at the free space center wavelength.

The expected pressure sensitivity at a Bragg wavelength λ_{Bo} of 1550 nm is $\approx 3\times10^{-3}$ nm/MPa.

2.3 FBG volumetric flow rate sensor

A uniform FBG volumetric flow rate sensor is represented by the following equation [6]:

$$Q = \frac{A}{(\lambda_{Bo} - \Delta\lambda_T)(1-p_e)} * \frac{d}{St} * \frac{\partial\lambda_B}{\partial t} * K_\lambda \tag{7}$$

Where;

Q is the volumetric flow rate m^3/s, temperature and vortex shedding effect compensated.

$$p_e = \frac{n_{eff}}{2}\left[p_{12} - v(p_{11} + p_{12})\right] \tag{8}$$

Where;

p_{11} and p_{12} = The components of the strain-optic tensor (constant values)

v = The Poison's ratio

n_{eff} = Effective refractive index of the fiber core at the free space center wavelength.

A = Cross sectional area of the pipe m^2

$\Delta\lambda_T$ = the fractional wavelength shift in nm due to temperature

$\frac{\partial \lambda_B}{\partial t}$ = The rate of change of the reflected wavelength nm/s

K_λ = Is a flow-optic conversion coefficient, (calibration constant).

d is the width of the Bluff body, constant value

3 New Multiphase Flow Metering Technique and Mathematical Modeling

As illustrated in figure (3), the proposed technique comprises of an upstream flow meter (FBG flow sensor) and a small size separation vessel. By diverting a part of the oil well flowing stream to the system, the upstream flow meter will always give the volumetric flow rate of the multiphase fluid passing through the meter before, hence a volume of the fluid before separation is always known. When the diverted flowing stream enters the separation vessel, the fluid separates into water, emulsion, oil and gas. The FBG distributed sensor arrays inside the separation vessel will continuously detect the hydrostatic pressure at different points and heights inside the separation vessel, the detected hydrostatic pressure will be inclusive of the gas pressure as well. From the measured values of hydrostatic pressure, gas pressure and temperature, the level of each phase of the fluid can be calculated. The volume of the separation vessel is known and the upstream volumetric flow rate was already known. Hence the volumetric flow rate of each phase of the fluid can be extracted. This done, the mathematical modeling of this technique is formulated as follows:

3.1 Measurement of the upstream volumetric flow rate (before separation)

This is calculated using equation (8) which states that the rate of change of the reflected FBG sensor wavelength $\frac{\partial \lambda_B}{\partial t}$ (nm/s) is proportional with volumetric flow rate Q (m^3/s).

3.2 Measurement of hydrostatic pressure of the separated phases

An array of uniform FBG sensors is simply a length of an optic fiber inclusive of multiple and cascaded FBG sensors written on the fiber core. Each FBG sensor has its own Bragg wavelength. As example for a fiber light source of 1300 to 1600 nm bandwidth, hundreds of FBG sensors can be written and occupy a 50 cm length of the fiber, each sensor will be operating on $2nm$ bandwidth or higher and its own Bragg wavelength. The reflected wavelengths form a single array of m number of sensors will take the notation of $\Delta\lambda_1, \Delta\lambda_2, ...\Delta\lambda_m$.

Where $\Delta\lambda_1$ is the reflected wavelength of the top sensor at the top point of the separation vessel and $\Delta\lambda_m$ is the reflected wavelength of the bottom sensor at the bottom point of the separation vessel.

For n numbers of sensor arrays, the reflected wavelength may write as:

$$\Delta\lambda_{n\times m} = [\Delta\lambda_P + \Delta\lambda_T]_{n\times m} \quad (9)$$

for $n = 1,2......,n$ and $m = 1,2,.......,m$

Where $\Delta\lambda_T$ is the wavelength shift in nm due to temperature and it is calculated using equation (4). d $\Delta\lambda_P$ is the wavelength shift in nm due to the hydrostatic pressure and is calculated using equation (9).

Hence, equation (12) may write as follows:

$$\Delta\lambda_{n\times m} = [\lambda_{Bo}(K_P\Delta P + K_T\Delta T)]_{n\times m} \quad (10)$$

for $n = 1,2......,n$ and $m = 1,2,.......,m$

ΔP is the hydrostatic pressure of the fluid plus the gas pressure of the vessel, may represented as follows :

$$\Delta P = \rho g H + P_G \quad (11)$$

For the separated multiphase fluid, equation (11) may write as follows:

$$\Delta P = \rho_1 g H_1 + \rho_2 g H_2 + \rho_3 g H_3 + P_G \quad (12)$$

Where;

ρ_1, H_1 are the oil density and Height respectively.

ρ_2, H_2 are the emulsion density and Height respectively.

ρ_3, H_3 are the water density and Height respectively, g is the gravitational constant.

3.3 Measurement of the volumetric flow rates of the fluid separated phases

At any sampling time, equation (10) and (12) gives $n\times m$ equations to calculate H_1, H_2, H_3 and P_G,

The physical volume of the separation vessel is known (constant value). Hence the individual volumes of the separated fluid phases and the gas volume can be extracted. Plus the upstream un-separated fluid volumetric flow rate were already measured using equation (7), hence the volumetric flow rate for each of the oil, water and gas can be obtained. Computational intelligence such as ANN and Fuzzy Logic would be required for the implementation of this technique.

3.4 Further design considerations

Because of the sensing passive optical components are passive ones of tiny sizes, the size of the separation vessel could be as small as possible. This makes the system installed on a well sampling line rather than the main line. Here, the aim is to make the design suitable and flexible for a wide varity of offshore oil wells installations. One system can cover multiple numbers of oil wells on the same platform by automatic and scheduled switching between well sampling lines, so a major drop in well testing can be achieved. The system can be connected and controlled via a Telemetry system so as unmanned operation and electronic data logging can be achieved.

4 Conclusion

A new technique for multiphase flow metering based on passive optical components “Fiber Bragg Grating Sensors “ has introduced and its mathematical algorithms have developed. This technique may provide higher accuracy of measurements compared to existing technique because of the high sensitivity of FBG sensors. Increasing the number of sensor arrays inside the separation vessel will further improve the accuracy. Computational intelligence to process and analyze the measured data would be required. Using passive fiber optic sensors achieves higher safety, electromagnetic interference immunity, noise reduction, and corrosion and erosion resistance.

References

[1] D. W. Spitzer, ISA, “Flow Measurements - Practical Guides for Measurement and Control “, ISBN 1-55617-334-2,1991.

[2] Andreas Othonos, Kyriacos Kalli, “Fiber Bragg Gratings - Fundamentals and Applications in Telecommunications and Sensing”, 2001.

[3] Raman Kashyap, “Fiber Bragg Gratings”, Optics and Photonics, 2001.

[4] D. S. Starodubov, V. Grubsky, J. Feinberg, "Ultra strong Fiber Gratings and Their Applications”, Dept. of Physics, University of Southern California.

[5] Richard Thorn, Geir Anton Johansen, Erling A Hammer,” Three-Phase Flow Measurement in the Offshore Oil Industry Is There a Place for Process Tomography? ", School of Engineering, University of Derby, DE22 1GB, UK.

[6] M Mahmoud- "New Crude Oil Flow Meter Design Based on Passive Fiber Optic Components”, Sheffield Hallam University, UK.

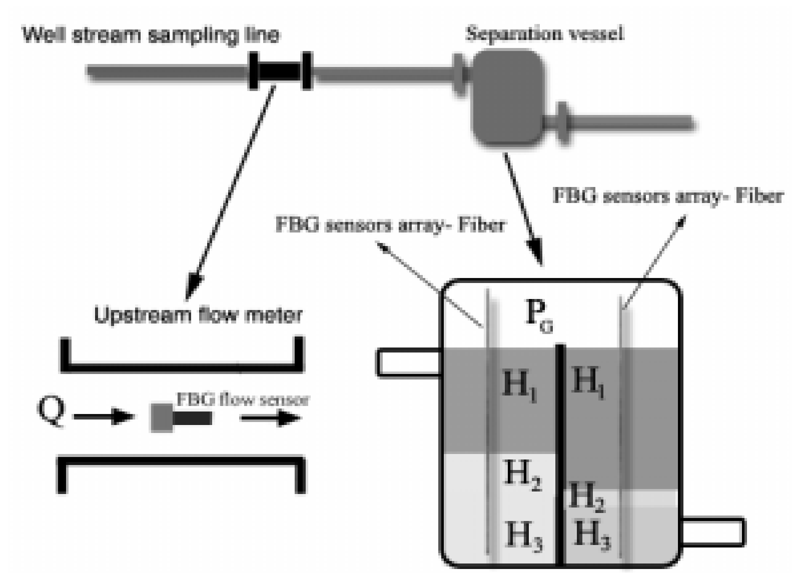

Figure (3) New Multiphase Flow Metering Technique