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A Comparative Study on Industrial Multiphase Flow Measurement Techniques

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ABSTRACT

Increasing demand for multiphase flow meters (MPFMs) in recent decades has resulted in intensive research to find innovative and advanced technologies that can be used for flow measurement. The overall issue is to design a cost-effective and durable solution that can provide real-time measurements of phase fractions and velocities in complex mixtures. This article aims at studying a number of such techniques being utilized for this purpose and provides the comparison of industrial flow meters that utilize these technologies based on their range of operation and measurement uncertainties.

Keywords: multiphase flow; gamma ray; tomography; magnetic resonance; inline metering

1. INTRODUCTION

There has been an increased necessity for multiphase flow measurement devices in the oil and gas production industry in the past few decades. Since 1980, several research organizations and oil production companies have employed various technologies for flow measurement, differing in designs and functionalities. Some of these flow meters are being used commercially with extremely positive outcomes [1] and are broadly divided into two categories as shown in Fig. 1. The conventional single phase metering systems (discussed in section 2.1) fully separate the constituents of the multiphase mixture, and then use phase-specific measurement techniques for each constituent. Such systems can provide sophisticated measurements of hydrocarbon production. On the other hand, multiphase flow measurement technology (discussed in section 2.2 and 2.3) enables the measurement of multiphase mixtures very close to the point of extraction of oil without the need for separation of each phase and also provides continuous supervision of the performance of extraction plants, helping in analyzing the shortcomings in real time. However, due to increased measurement uncertainty in such measurements, a careful study is required to select an optimal multiphase flowmeter for a particular application, taking into consideration the installation costs and benefits it would provide (discussed in Section 3) [2]. This motivated us to provide an overview of the various flow measuring techniques and present a comparative study which would help the researchers working in this area.

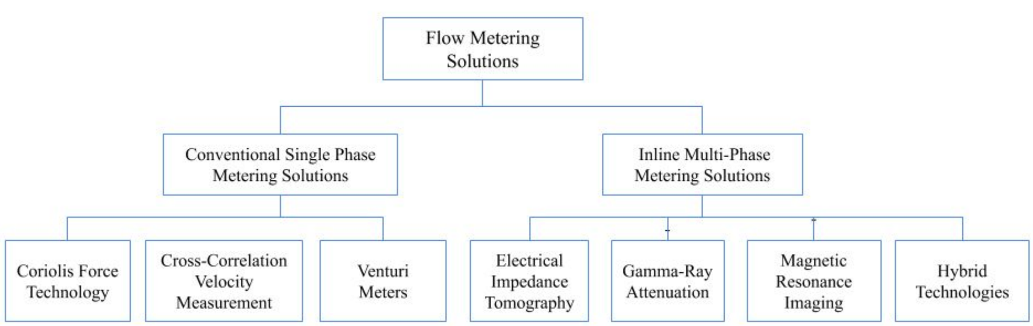

Figure 1 : Classification of Industrial Flow Metering Solutions

2. DISCUSSION

In this section, single-phase and inline multiphase flow metering are discussed first and then flow measurement methods are compared based on their accuracy of measurement and range of operation.

2.1 Conventional Test and Separator Arrangement using Single Phase Metering Systems

The conventional technique used for multi phase flow measurement is shown in Fig.2. It involves two major steps, first, the separation of flow into its components and then using single phase flow meters to measure each phase separately [2]. Some commonly used single phase flow meters for this purpose are venturi meters, turbine meters and coriolis flow meters [3].

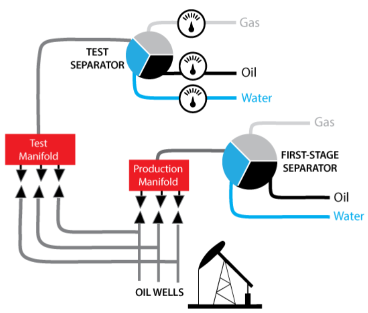

Figure 2: Setup of Conventional Test and Separator Arrangement

2.1.1 Flow Rate by Coriolis Force Technology

Coriolis flow meter is widely used to measure the mass flow rate in many fields of research and industry, Emerson Micro Motion is one such series of flowmeters that has concentrated on coriolis principle because of its highly accurate measurements and good repeatable characteristics. The working principle of Coriolis flowmeter relies on the Coriolis effect generated by the fluid flowing through the vibrating tubes [4, 5]. A Coriolis flow meter shown in Fig. 3 contains a tube which is energized by a fixed vibration. When a fluid (gas or liquid) passes through this tube the mass flow momentum will cause a change in the tube vibration, the tube will twist resulting in a phase shift.

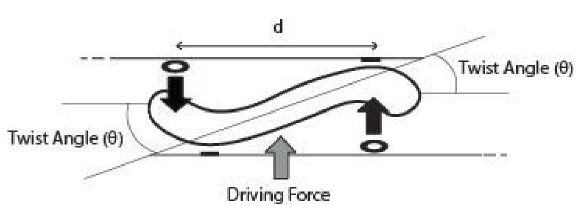

Figure 3: Schematic Diagram of Coriolis Flowmeter

If ρ, ω, and the meter's cross-sectional area are held constant, then the twist angle (amplitude of deflection) is proportional to the mass flow rate of the fluid flowing through the meter. Equation (1) provides the flow rate of fluid.

$$q_m = \frac{K_s \cdot \theta}{2 \cdot L \cdot d \cdot \omega} \quad (1)$$

2.1.2 Tomography or Cross – correlation velocity measurement

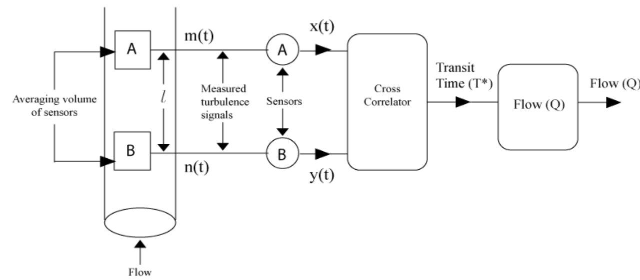

Figure 4 : Schematic diagram of Cross- Correlation Velocity Measurement Setup

Fig. 4 shows the measurement setup for cross-correlation velocity. An important problem that tomography can solve is the measurement of phase fractions and velocities in challenging mixtures like highly polluted liquids, and extremely hot gases and liquids [6]. Tomography based cross-correlation velocity measurements rely on calculating the transit time of signals passing through the multiphase mixture obtained from separated sensors. The sensors involved in this process are ultrasonic sensors, electrostatic and capacitive sensors etc. [7].

2.1.3 Differential Pressure : Venturi Meter

Differential pressure transmitters (DPTs), which can find the difference in pressure measurements at two different points in the flow of multiphase fluids are used widely in many MPFMs. DPTs are essentially based on the equation of continuity and Benoulli's equation [8]. Venturi meters (shown in Fig. 5) and orifice plates are DPTs which utilize the fact that, reducing the area of flow can increase the velocity and thus substantially reduce the pressure at particular points.

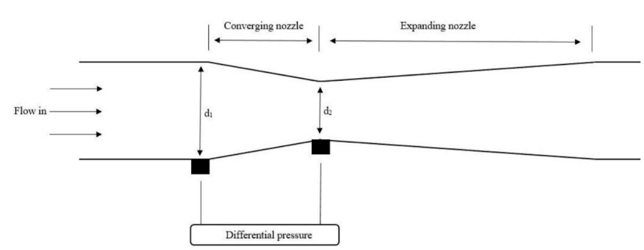

Figure 5: Principle of a Venturi Meter [9]

We limit our discussion to venturi meters as it has the lowest pressure loss compared to other DPTs [9]. In a Venturi meter, the differential pressure obtained is proportional to the kinetic energy of the mixture passing through and the volumetric flow rate Q, is given in (2): [10]

$$Q = A \cdot v = C \cdot e \cdot E \cdot \pi \cdot D^2 \sqrt{\frac{2 \cdot \Delta P}{\rho}} \qquad (2)$$

DPTs have found extensive use in Halliburton's MPFMs

2.2 Advances to Multiphase Flow Measurement

Conventional test and separator arrangement requires a significant number of valves, piping and duplicate instrumentation on each separator. Due to redundancy and limitations in the conventional setup, one for one arrangement (shown in Fig. 6) is considered in which each has its own dedicated separator and measurement system. This setup has significantly less piping, requires less manual intervention and provides continuous real time measurement instead of periodic testing and results in a cost-effective and reliable solution.

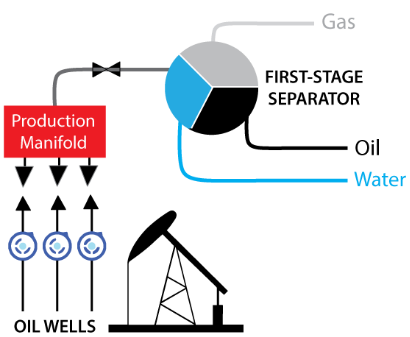

Figure 6: Setup of an Inline Multiphase Metering System

2.3 Inline Multiphase Metering Solution

In order to determine the volumetric flow of oil, water and gas, the velocity of all three phases must be measured as well as the fraction/composition of each phase in the pipe void is needed and the equation is given in (3).

$$Q_{phase} = v_{phase} \cdot A_{phase} \qquad (3)$$

To appreciate the concept of Inline metering, it is necessary to understand the parameters involved in it. A set of four equations (4) to (7) relates the mixture's permittivity, conductivity and density to the corresponding parameters of individual phases.

$$\alpha + \beta + \gamma = 1 \qquad (4)$$

$$\varepsilon_{flow} = f(\alpha\varepsilon_{gas}, \beta\varepsilon_{liquid}, \gamma\varepsilon_{oil}) \qquad (5)$$

$$\sigma_{flow} = g(\alpha\sigma_{gas}, \beta\sigma_{liquid}, \gamma\sigma_{oil}) \qquad (6)$$

$$\rho_{flow} = h(\alpha\rho_{gas}, \beta\rho_{liquid}, \gamma\rho_{oil}) \qquad (7)$$

Solving any three of the equations given in (4) to (7), the fractions of permittivity, conductivity and density of each phase can be obtained. A number of scientific methods that have been applied to solve this set of equations, a few of which are impedance measurement, Gamma ray attenuation and magnetic resonance and are discussed in the following subsections [1].

2.3.1 Electrical Impedance Tomography

A leading technology used is electrical impedance tomography (EIT), which consists of two parts, capacitance measurement and conductance measurement. A schematic setup for this arrangement is shown in Fig. 7

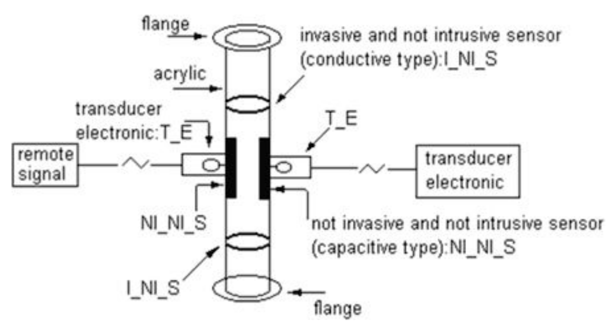

Figure 7: Schematic setup of Impedance Measurement in Multiphase Flow [11]

Capacitance in the pipe void is related to the permittivity of the oil/gas/water mixture. The permittivity for hydrocarbons is much less than that of water and thus the measured permittivity can be used to split hydrocarbons and water.

$$C = \varepsilon_r \cdot \varepsilon_o \cdot \frac{A}{d} \qquad (8)$$

Conductance is the measure of the ability of a solution to conduct electric current, it is the reciprocal of electrical resistance and is calculated by measuring current and voltage drop across the electrodes. By measuring both the current and the voltage drop, the resistance is calculated using Ohm's Law and hence the mix conductance is as given in (9).

$$\sigma = \frac{1}{R} = \frac{I}{V} \qquad (9)$$

Thus, impedance measurement provides the solutions to the set of equations, and the phase fractions of the components of the mixture.

2.3.2 Gamma Ray Attenuation

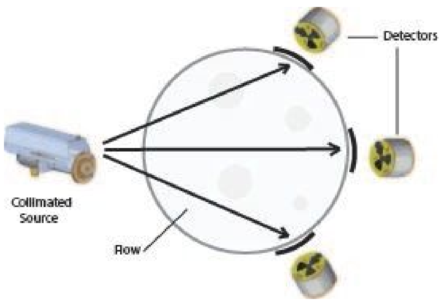

Figure 8: Schematic Head-on Setup of Multi-beam Gamma Ray Attenuation

Schlumberger uses another technique which relies on measuring the decay of gamma rays when passed through a fluid. In cases where the gas volume fraction exceeds 0.85, gamma ray attenuation method can be used to solve the system of equations. Fig. 8 shows a typical multi-beam gamma ray attenuation arrangement. It is based on the principle that gamma radiation's intensity decreases exponentially when it passes through the matter as expressed in (10).

$$I_N = I_0 \cdot e^{-K \cdot \rho \cdot N} \tag{10}$$

Knowing the strength of the radioactive source and measuring the gamma radiation with a detector on the other side of the media shall give us the density of the media [12] [13].

2.3.3 Magnetic Resonance Signal Decay and Imaging

Hydrogen is the common component of hydrocarbons, gases and water and using magnetic resonance imaging would be another alternative in flow measurement. The multiphase mixture is first magnetised and subsequently excited by pulses of radio frequencies. Fig. 9 shows the process of magnetisation of hydrogen atoms.

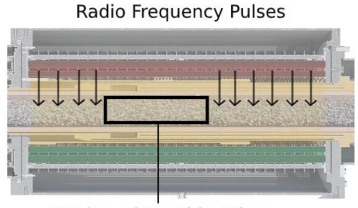

Figure 9: Schematic Setup of MR Signal Decay System

The hydrogen atoms of the different phases respond to these pulses and send back echoes which are recorded by sensors. The amplitude of the echoes and the rate at which they decay is used to calculate the flow rates of oil, gas and water.

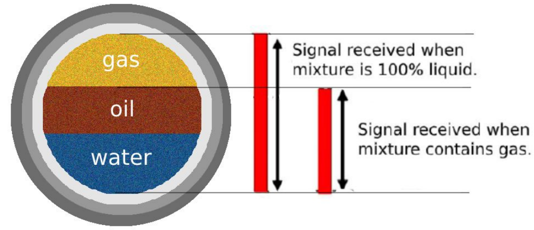

Figure 10: Head on view of Gas Fraction Calculation.

As illustrated in Fig. 10, it is observed that there is a difference between the theoretical signal to be received and the actual signal received, this is due to the fact that flow is divided into oil, gas and water, the missing signal corresponds to the gas fraction. A fundamental difference between oil and water is, oil magnetizes very quickly as compared to water. According to the number and density of magnetization, the phase fractions of oil and water can be obtained. Looking head-on to the flow of liquid, velocities per small slices are observed and magnetic resonance imaging is performed to obtain the amplitude and velocity of the 16 individual slices. From which the fractions of gas, oil and water and also the velocities of each of the phases can be obtained as shown in Fig. 11.

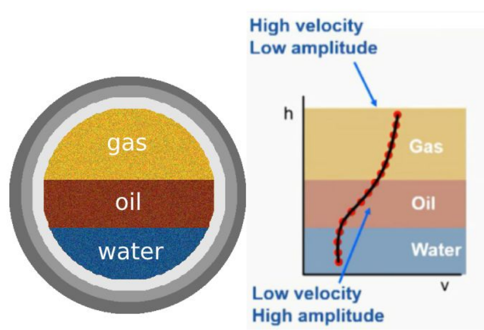

Figure 11: Head-on Schematic Diagram for Magnetic Resonance Imaging

The gas fraction is calculated from the 'missing' signal, moving onto differentiation between oil and water. KROHNE Oil and Gas series of flowmeters are one such example of meters that utilize this technology [18].

2.3.4 Hybrid Multiphase Metering Technologies

Continuous research in the field of multiphase flow measuring technologies have led to the development of hybrid MPFM, which combines two or more flow measurement principles. Flowmeters by Weatherford and Pietro Fiorentini have utilized this scheme, and have been amongst the most accurate ones. Weatherford utilized Venturi meter, gamma decay and sonar array as its working principles while Pietro Fiorentini utilized EIT along with Venturi meter and gamma decay principle.

2.4 Performance Comparison of Industrial Flow Metering Solutions

Various technologies utilized for flow measurement are discussed in the previous section. A comparison of different industrial flow meters based on their principle of operation, operating range and measurement uncertainty is presented in Table 1. The comparison is based on the data obtained from the manufacturer's data sheets.

Table 1: Principle of Operation, Range and Uncertainty Measurements of Industrial MPFMs

Industrial MPFM Series	Principle of Operation	Range WLR GVF	Uncertainty Liquid Gas Water cut
Emerson Roxar 2600 M [14]	EIT	0-100 % 0-85 %	± 3 to 5% R ± 6 to 8% R. ± 2 to 4% A.
Weatherford Red-Eye [15]	Venturi, Gamma, NIR Spectroscopy	0-100 % 0-100 %	± 5% ± 5% ± 2%
Schlumberger Vx Spectra [16]	Gamma	0-100 % 0-100 %	± 5%
Pietro Fiorentini Flowatch HS [17]	Venuri, Gamma, EIT	0-100 % 0-97 %	± 3% R ± 5% R ± 2% A.
KROHNE M-Phase 5000 [18]	Magnetic Resonance	0-100 % 0-98 %	±3 to 5% ± 8 to 10% ± 3 to 5%
Agar - 50 [19]	Microwave, Venturi and Coriolis Force	- 0-100 %	+ 5% + 5% + 5%
Haimo Spool Piece [20]	Venturi, Dual - Gamma	- 0-95 %	± 5 % R ± 10 % R. ± 3 to 5%A

R: relative, A: absolute, N.A: Not available, WLR: Water Liquid Ratio, GVF : Gas Void Fraction, - : Data not available

Based on technologies utilized, it can be generalized that EIT and gamma densitometry methods provide encouraging results and work exceptionally well together. It can also be observed that Emerson (Roxar) 2600 M and KROHNE Oil and Gas, have no radioactive sources and have relatively higher uncertainty measurements than other MPFMs. Pietro Fiorentini's Flowatch HS and Weatherford Red-Eye MPFM, both utilizing hybrid models combining a variety of measurement techniques along with radioactive sources have robust operating range as well as low uncertainty in measurements.

3. CONCLUSIONS

One of the greatest benefits of using MPFMs is that it can help monitor productivity of oil extraction by calculating the fraction of hydrocarbons being extracted. MPFMs can also help an organization to predict the lifetime of an extraction project by estimating the oil production by simulating the extracted output through the years of production. After studying numerous MPFM technologies, it is observed that conventional meters offer less uncertainty in measurement compared to inline metering flow meters. However, it shall also be noted that the cost of installation of conventional flow meter exceeds that of Inline multiphase meter by almost 50 %. Even though most oil wells prefer to use inline multiphase metering due to its cost benefits, considering the reservoir accuracy required, it would be better to opt for conventional methods as is the case with challenging reservoir management in high hydrogen sulfide conditions in Kazakhstan, which require greater levels of accuracy. More advanced metering and measurement technologies are needed in the coming decades, especially looking to improve the accuracy of inline multiphase flow meters.

NOMENCLATURE

A	Area	(m^2)
C	Discharge coefficient	-
e	Expansibility factor	-
d	Distance between applied forces	(m)
D	Diameter of the throat	(m)
E	Beta factor unit	-
I	Induced Current	(Amp)
I_N	Intensity of radiation after passing through mixture	(W/m^2)
I_0	Initial Intensity of radiation	(W/m^2)
K	Calibration constant	(m^2/kg)
K_s	Spring coefficient	(N/m)

L	Axial length of one leg	(m)
N	Length of Gamma Beam	(m)
ΔP	Difference in Pressure	(N/m^2)
Q	Volume Flow Rate	(m^3/s)
R	Electrical resistance	(Ω)
v	Flow velocity	(m/s)
V	Measured voltage	(V)
ε_r	Relative permittivity of a medium	-
ε_o	Permittivity of free space	(F/m)
ρ	Density of mixture	(kg/m^3)
θ	Twist angle	$(radian)$
ω	Angular momentum	$(kg.m^2/s)$

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