# AN INVESTIGATION OF EFFECTS OF FLOW CONDITIONING ON STRAIGHT TUBE CORIOLIS METER

A Thesis

by

SHASHANK SHUKLA

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 2008

Major Subject: Petroleum Engineering

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Approved by:

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| Chair of Committee, | Stuart L. Scott |
| Committee Members, | Gioia Falcone |
| | Gerald Morrison |
| Head of Department, | Stephen A. Holditch |

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# ABSTRACT

An Investigation of Effects of Flow Conditioning on Straight Tube Coriolis Meter.

(May 2008)

Shashank Shukla, B.Tech, National Institute of Technology, Calicut, India

Chair of Advisory Committee: Dr. Stuart L. Scott

Coriolis meter, despite being very accurate in single phase conditions, fails to accurately measure two-phase flows. It poses a complex fluid-structure interaction problem in case of two-phase operation; there is a scarcity of theoretical models available to predict the errors reported by Coriolis meter in aforementioned conditions, hence the need for experimental research.

Experiments are conducted in both single and two-phase flow conditions. Meter accuracy is excellent in single phase conditions and no significant effect is observed on use of flow conditioners, namely inlet swirl and inline mixer. Operational two-phase envelope is determined through experiments at different flowrates. Flow conditioners are used to study the effect of phase segregation and homogenization on accuracy of the meter. Testing is done to cover two-phase flows from both extreme ends, namely aerated liquids and wet gas. Use of flow conditioners show slight improvement in meter accuracy on use of inline mixer, and reduction in accuracy in case of inlet swirl, when both former and latter are compared to results obtained from experiments with no flow conditioners. The difference in accuracies between results with flow conditioner and without flow conditioners is attributed to relative motion between the phases, which is more in case of inlet swirl, due to larger bubble sizes. Flow conditioners show an insignificant effect on meter accuracy during wet gas tests. The reason proposed is annular flow regime, which is not highly affected by flow conditioners.

Single phase tests demonstrate that Coriolis meter gives accurate measurement even in presence of severe flow disturbances. There is no need for flow conditioning before the meter to obtain accurate readings from it, which would be the case in other metering technologies like orifice and turbine. In two phase flows, the meter reports negative errors, which is consistent with previous experimental works available in literature. Use of flow conditioners clearly affects the reading of the meter in aerated liquids. This phenomenon can be used to get fairly accurate estimate of flow rate in low gas volume fraction liquid flows.

# DEDICATION

I dedicate this research effort to my brother-in-law, Mr. Ashutosh Mishra, and my sister, Mrs. Shipra Mishra. Due to their constant support and affection, I was able to continue my education.

# ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Scott, for his support and encouragement throughout the duration of this work. He has been ideal mentor and I could not have asked for better. I would also like to very much thank Dr. Falcone and Dr. Morrison for their guidance and support.

Thanks also goes to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience, especially Amol Dixit, Austin Gascamp, Deepam Tiwan, Fouad Solomon, Gretchen Fudge, Issac Ekoto, John Boham, Jose Baker, Joshua Davis, Kharli Mootz, Luciana Cruz, Sukesh Shenoy, Sumanth Panda, Sunny Jain, Vaibhav Deshpande, Varun Mishra and Xian Xu, to name a few (in strict alphabetical order!).

Finally, thanks to my parents, Dr. Chitra Shukla and Dr. Krishna Kant Shukla, for their encouragement and understanding of my absence from home for more than two years.

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# CHAPTER I

# INTRODUCTION

## 1.1 Background

The measurement of multiphase flow with good rangeability and acceptable accuracy will be a very cost effective solution for the development of new satellite fields as well as for optimization of existing fields[1]. Multiphase metering technology has advanced quite significantly over past few years, as has the acceptance and utilization of such technology both onshore and offshore.

Many new fields are economically marginal and cannot sustain the financial implications of the traditional separator based technology. Multiphase meters can offer substantial cost savings by eliminating the need of separators, or by allowing several fields to share common processing facilities.

In well management applications, multiphase meters offer continuous data output giving valuable information about the performance of the wells. This enables problems or changes in well performance to be detected sooner, and subsequent interventions planned earlier than would be possible with traditional processing technology.

The importance of multiphase metering is evident in the number of papers published on the subject and the time devoted to it at major flow measurement and oil and gas conferences.

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This thesis follows the style and format of *SPE Journal*.

Within the oil and gas industry, it is generally recognized that multiphase metering can be very beneficial for the following[1, 2].

### 1.1.1 Layout of production facilities

Use of multiphase meters reduces the hardware needed for onshore, offshore topside and offshore subsea applications by eliminating the need of dedicated test separator for well testing applications. With a smaller "footprint" it minimizes platform space and load requirements. It also makes the costly well test lines obsolete; which is very important for unmanned locations, deepwater developments and satellite fields.

### 1.1.2 Well testing

Well testing using multiphase meters is much quicker than by traditional separator. Multiphase phase meters have accuracy comparable to conventional test separators (~5-10%)[2], but the latter require regular intervention by trained personnel and cannot provide continuous well monitoring. Another disadvantage of using conventional well testing with separators is that wells suffer from regular shutdown cycles related to well testing; this may lead to more frequent workovers needed to maintain their production rates. Multiphase meters can also be used to measure clean up flow after exploratory drilling; added value may include improved control of drawdown applied to the formation, the pressure transient and shortened flow periods.

### 1.1.3 Reservoir management

Multiphase meters can provide real time, continuous data for the operators to better characterize field and reservoir performance and to react faster. Using multiphase meters in individual wells can be a powerful tool in field development. It can help singling out the “under-performing” wells, and to plan interventions. Any appreciable changes in productivity index, gas-oil ratio and water cut can be detected and quantified almost immediately, as opposed to conventional test separators where this information is at discrete points in time and on cumulative volume basis.

### 1.1.4 Production allocation

Using multiphase meters in manifolds handling commingled production from different fields/wells operated by different companies holds clear advantage over the conventional testing. In the latter, production from each well must flow through a test separator before commingling with other produced streams. This especially is a formidable task in planning tie-backs for existing facilities.

### 1.1.5 Production monitoring

Real time monitoring of production data from multiphase meters can give useful information for detecting problems associated with well slugging and gas-lift issues. This allows operators to optimize well performance and extend field life.

### 1.1.6 CAPEX and OPEX

Apart from direct savings in CAPEX for multiphase meters compared to conventional test separators, the OPEX of multiphase meters is also estimated to be considerably lower than the latter. In addition, it is estimated that multiphase metering systems could improve the management of the field/well with 6-9%[2] gain in the value of the oil recovered. Both CAPEX and OPEX for multiphase meters are estimated to reduce as competition in the market increases and more operational experience is gained.

### 1.1.7 Fiscal metering or custody transfer

Current technology in multiphase metering is not accurate enough for fiscal metering. Custody transfer metering is still being done single phase metering devices, used after separating the phases. Considerable research and development work is however being done in improving the accuracy of multiphase measurement.

A large number of technologies are available to measure multiphase flows. Most of the multiphase meters are combination of techniques each giving parameters, which together can give individual flowrates and volume fraction. Due to large costs associated with multiphase meters, a lot of attention has been given to single phase meters (which are comparatively inexpensive) operating in multiphase conditions. One of such candidates is Coriolis meter.

Coriolis mass flow and density meters are considered the flow metering solution of choice for many precision flow applications. Coriolis mass flow metering has been used in industry since early 1980s; since then Coriolis meters have grown into one of the largest and fastest growing meter segment, representing roughly $400 million annual sales on approximately 100,000 units[3].

Coriolis mass flow meters are available in widely varying designs (e.g. straight-through pipes, U-tubes, B-tubes, with single path or split flow configurations), but the operating principle remains the same: mass flow through a vibrating tube causes a proportional Coriolis force to act, which is detected as a phase difference between two velocity sensors. Almost all transmitter designs cause the flowtube to vibrate at its natural frequency; this frequency is a function of the process fluid density, which can thus be calculated and given as an additional measurement. The process fluid temperature is also measured to provide temperature correction of the mass flow and density (compensating for tube stiffness), and as an extra process measurement. Coriolis meter is thus a fairly sophisticated example of a multivariable industrial sensor.

Coriolis meters offer several advantages over other flow rate measurement technologies. They have accuracy and repeatability of 0.2% or better, and the ability to handle difficult, non-Newtonian fluids such as slurries and food stuffs[4]. There are also limitations associated with them. Currently Coriolis meters are very expensive to buy and install. Another major disadvantage is the impact of two-phase (gas-liquid) flow on meter performance. Even a short burst of gas in a liquid flow stream may cause serious disruption to meter operation and lead to large measurement errors[5].

In the past, research and design efforts to improve the performance of Coriolis mass flow meters have concentrated on areas such as digital signal processing; separation of phases using compact separators, design of tubes among others. Very few public domain literature concerns with effect of flow conditioning on performance of Coriolis meters operating in single phase flows. To the best of author’s knowledge, no one has reported effect of flow conditioning on Coriolis meter in two-phase flows. A good understanding of latter will aid in the design of multiphase metering packages incorporating Coriolis meter and ultimately, confidence in its use.

## 1.2 Literature review

Domnick et al (1987)[6] states and gives arguments, that in case of multiphase flows, Coriolis mass flow meter will be accurate when the secondary phase particles/droplets/bubbles in the flow follow the oscillations of the measuring instrument (and the primary phase). In the presence of axial swirl, one is forcing the suspended particles (or bubbles/droplets) to move in a fashion different from that dictated by the vibration of the sensor tube. This phenomenon predicts a degraded performance of Coriolis meters in presence of axial swirl though, they haven’t looked particularly into the effect of axial swirl particularly.

Cascetta et al (1989)[7] describe a new design of Coriolis mass flow meter, which permits measurements independent of the elastic properties of the vibrating tube. The measuring principle is suitable for metering homogeneous or heterogeneous two-phase fluids. For the latter the density of the secondary phase should not be too different from that of primary phase, so that when the sensor tube is set in relative motion the two phases may behave as rigidly connected. Cascetta et al (1992)[8] experimentally compared performance of seven Coriolis mass flowmeters. They also outlined some of the external factors which might affect accuracy of Coriolis mass flow meter, including but not limited to various turbulence spectra and presence of axial swirl. No explanation, as of what might be the effect of axial swirl on Coriolis mass flow meter would be, is presented.

Hemp and Sultan (1989)[9] developed a “bubble” model for Coriolis mass flow meters operating in two-phase regimes; considering the inertial losses generated by a single bubble surrounded by much denser liquid, passing through vibrating tube. This model predicts monotonic, negative errors which are a function of gas void fraction (GVF) only, i.e. the proportion of gas by volume in the two-phase mixture. Mass flow and density errors specifically take following form [10],

$$\frac{\dot{m}_{observed} - \dot{m}_{true}}{\dot{m}_{true}} = \frac{-2\alpha}{1-\alpha} \quad \text{.......} \quad (1)$$

$$\frac{\rho_{observed} - \rho_{true}}{\rho_{true}} = -3\alpha \quad \text{.......} \quad (2)$$

Where $\dot{m}$ is the mass flow rate of the combined stream, and $\alpha$ is the gas volume fraction on a scale of 0 to 1. This model was then compared to measurements by Grumski and Bajura (1984)[11]. The theory overestimated the errors and the reason provided was possible interaction between bubbles.

Tests of single-tube and dual-tube Coriolis meters in liquid flows by Grumski and Bajura (1984)[11] found that the meters could measure single-phase mass flow rates to within ± 0.4% of the actual. Air was then injected into the water flow to test the tolerance of the Coriolis meters to entrained air. The single tube meter gave mass flow readings accurate to within ± 2% for flows up to 1.5% gas by volume, then its accuracy dropped until complete failure occurred between gas volume fractions of 2.5% and 3.5% (**Fig. 1.1**).

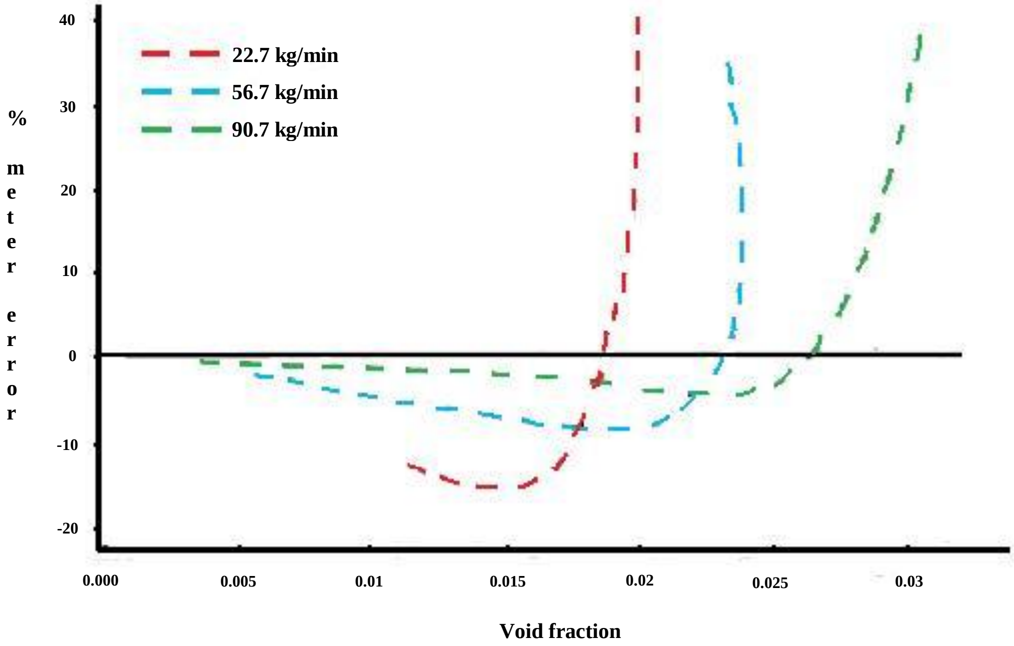


**Fig. 1.1 – Single tube Coriolis meter accuracy under aerated liquid tests[10].**

The dual tube Coriolis meter fared better; errors of less than ± 2% were observed for gas volume fractions below 7.5%, and failure occurred between gas volume fractions of 16% to 20% (**Fig. 1.2**).

Benefits of using one particular design of Coriolis meter over others are also scarcely reported. Al-Khamis et al[12] reported that straight tube Coriolis mass flow meter is less sensitive to gas entrained in the liquid than both U-tube and the modified form of U-tube Coriolis mass flow meter for the range that was tested (**Fig. 1.3**). The reason given for this observation was less pressure drop in straight tube Coriolis mass flow meter; due to which less amount of dissolved gas comes out of the solution. Straight tube Coriolis meter was also able to handle higher two-phase flowrates than other designs.

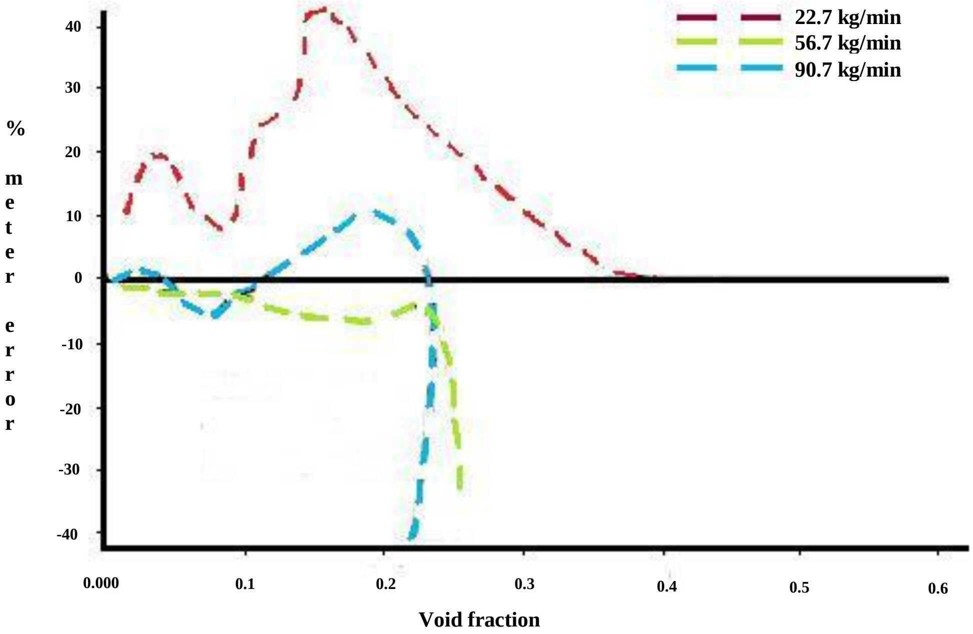


**Fig. 1.2 – Dual tube Coriolis meter accuracy under aerated liquid tests[10].**

Recently several research efforts have been done trying to predict Coriolis meter performance in two-phase flows[13]. Gysling[14] proposed a lump model of Coriolis meter operating in aerated flows. He gives arguments showing importance of speed of sound measurement in Coriolis meters due to acoustic resonance of the fluid in the tube, mainly in relation to their density measurements. It is proposed that an additional measurement of speed of sound in multiphase mixture will enable predicting accurate density of the process fluid. Gysling[3] presented an improved comprehensive lumped parameter, aeroelastic model of U-tube Coriolis massflow and density meter addressing the issues of compressibility and inhomogeniety present by aerated process fluids. He shows that the behavior of the meter is influenced by several parameters like void fraction, fluid viscosity and reduced frequency. As in previous work[14], speed of sound in aerated fluid is measured as an additional variable and is used to calculate all aeroelastic operating parameters, gas volume fraction and reduced frequency. They also discuss process of relative motion between the bubbles and the liquid, and how this can cause damping and a change in the apparent density of the mixture. This methodology has been successfully used in recent field experiences [15, 16].

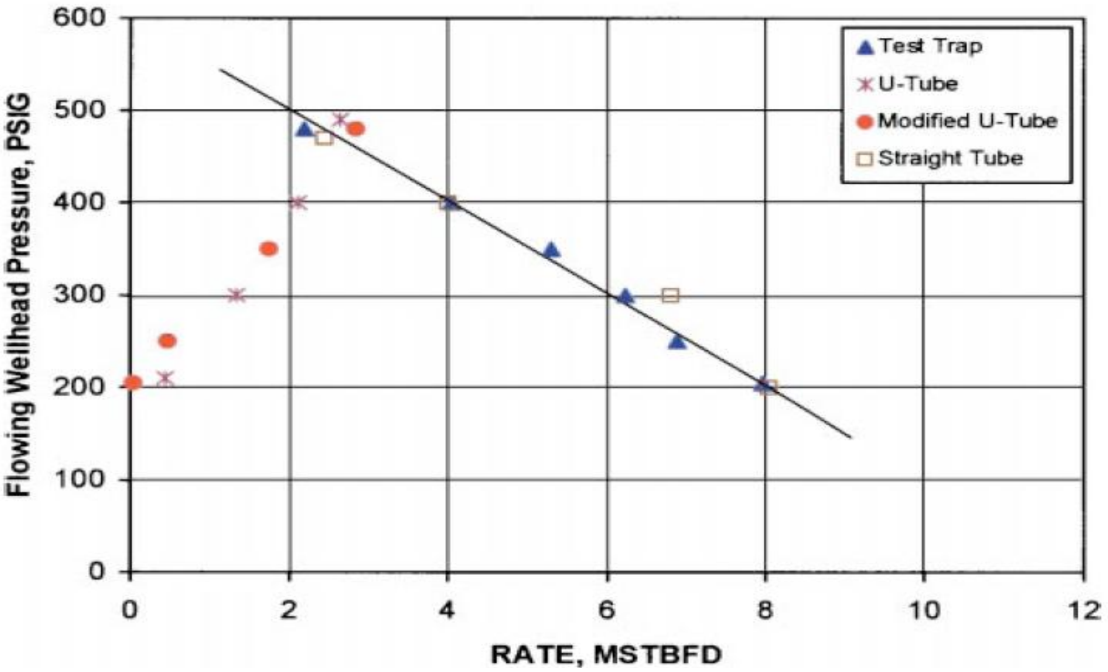


**Fig. 1.3 – Comparison between straight tube and U-tube design. Straight tube Coriolis meter is able to handle higher two-phase flow rates than U-tube[11].**

Hemp and Kutin (2006)[17] investigated both massflow and density errors associated with Coriolis meter operating on compressible fluids. Their analysis is applicable to small fractional errors (low contamination of secondary phase) and as such does not cover the full range of two-phase flows from aerated liquids to wet-gas. They propose following expressions for massflow and density errors encountered in case of compressible fluids,

$$\frac{\dot{m}_{observed} - \dot{m}_{true}}{\dot{m}_{true}} = \frac{1}{2}\left(\frac{\omega_1}{c}b\right)^2 \qquad (3)$$

$$\frac{\rho_{observed} - \rho_{true}}{\rho_{true}} = \frac{1}{4}\left(\frac{\omega_1}{c}b\right)^2 \qquad (4)$$

Where $\omega_1$ is resonance frequency of the flowmeter tube filled with compressible fluid, b is the flowmeter tube radius (inner) and, c is the velocity of sound in fluid.

Investigation of effect of inlet velocity profiles on Coriolis meter performance has also been done for single phase flows by researchers. Cheesewright et al (2000)[18] identified external factors which influence the calibration of Coriolis massflow meter. Tests were conducted where they found no significant (>0.25%) effect of inlet swirl conditions on the three Coriolis meters used in tests; also the effect of severely asymmetric inlet velocity profiles (50% blockage immediately upstream of the meter) was minimal. Bobovnik et al[19] investigated the effect of fully developed, asymmetric triangular and swirl flows (introduced at the inlet) on the straight tube Coriolis meter using CFD analysis. They found that the effect of inlet swirl flow is not negligible only for the highest Reynolds number simulated. Similarly the effect of asymmetric triangular inlet condition was minimal (~0.1%) on the performance of the meter for the whole range of Reynolds number simulated. Recently Kutin[20] discussed velocity profile effects on Coriolis meters. Results showed Coriolis meter is sensitive to inlet velocity profiles; as in other investigations the effect observed was minimal.

In past other benefits of Coriolis massflow meters have been widely reported. Cox[21] showed that Coriolis meters can be used to satisfactorily measure oil/water emulsions. He also demonstrated the calibration is independent of the rheological nature of the fluid. Andersson and Gudmundsson[22] used Coriolis meter to measure flow rates of hydrate-water slurries. They noted that the meter gives accurate readings till the concentration of hydrate in water is less than 15%.

Another interesting development in multiphase metering using Coriolis meters is emergence of relatively inexpensive multiphase metering systems using compact separation systems along with Coriolis meters to measure fully or partially separated fluid streams, considerable research efforts are being undertaken to improve the separation capabilities of compact separator in order to improve the operational envelope of the system[23,24]; an example of such a system is shown in **Fig. 1.4**. This is a primary application of results obtained through testing Coriolis meters in swirl conditions, since the compact separators can experience phenomenon of gas carry under, where due to large centrifugal forces, gas phase may develop swirl characteristics. Another good application of inlet swirl will be installation of Coriolis meter after any bend or elbow where partial phase separation occurs due to the difference in the velocity profiles of two phases.

**Fig. 1.4 – Multiphase metering system using compact separation and Coriolis meters (from Phase Dynamics)**.

Recently Hemp and Yeung (2003)[10] provided a novel Coriolis transmitter technology developed at Oxford University, which they propose, can be accurate in measurement of aerated liquids. Difficulty encountered in accurately measuring aerated fluids is probably the most critical issue with Coriolis technology. Companies providing Coriolis meters suggest removing as much air from flow stream as possible before measuring it with Coriolis meter, but it is not generally the case. In most cases it is prohibitively expensive to bring air levels below admissible. There is a need for intensive research to devise methods to increase the permissible operation envelope of Coriolis meter measuring aerated fluids or wet-gas. Flow conditioning of fluids before they enter Coriolis meters can be an approach to attain the goal.

## 1.3 Objectives of the research

The purpose of this research effort is to observe the effect of flow conditioning on the mass flow and density measurement of a two phase flow by a straight tube Coriolis meter. This involves quantifying errors observed in mass flow and density measurement upon, introduction of air in fluid flow (aerated liquid) and introduction of liquid in air flow (wet-gas) with and without flow conditioning. Flow conditioning will be done using both swirl generator (phase segregation) and inline mixer (phase homogenization).

## 1.4 Thesis outlook

The physical geometry and operational features of Coriolis meters will be described next followed by a discussion of the applications and performance of Coriolis meters. Limiting physical phenomenon associated with Coriolis meters will be described. A general overview of experimental facility and process is given.

The effect of flow conditioning on the mass flow and density errors observed in two phase flow are compared with base cases (single phase, with and without flow conditioning) and presented. Analysis of the results obtained from this investigation compared to analytical models available in literature is reported.

Finally, conclusions and recommendations deduced from the outcome of this research are outlined.

# CHAPTER II

# PHYSICAL GEOMETRY AND OPERATIONAL FEATURES OF CORIOLIS METERS

## 2.1 Physical geometry of Coriolis meters

Coriolis meters are essentially aeroelastic devices; and as such involve coupled dynamic interaction of fluid dynamics and structural system. The Coriolis meter basically consists of a tube conveying fluid (lying in one plane and clamped at its ends) and associated circuitry. Circuitry includes an electromagnetic drive generally at the middle of the tube, and two electromagnetic detectors. It also includes a feedback circuit for maintaining vibration at the fundamental frequency and electronic means of measuring the phase difference (due to flow) between signals received from the detectors.

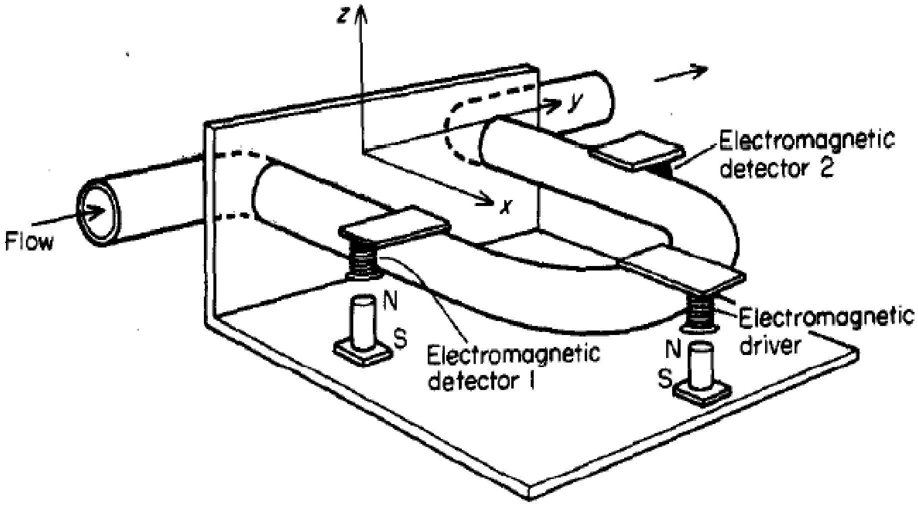


**Fig. 2.1 – A Coriolis mass flowmeter of U-tube configuration**.

## 2.2 Operational features of Coriolis meters

In the Coriolis mass flowmeter, an angular movement is imparted to a tube conveying fluid by means of electromagnetic drive. This angular movement is generally harmonic in nature though some earlier designs used steady rotation. This additional motion communicated to the flowing fluid causes the particles of fluid to undergo Coriolis acceleration. As a result forces proportional to the product of the fluid density and velocity act through the fluid medium and generate pressure on the conduit walls, producing a measurable effect.

$$\vec{a}_c = -2\vec{\omega}\times\vec{v} \qquad \text{……………………………………………………………………….} \quad (5)$$

Where $\vec{a}_c$ is the Coriolis acceleration, $\vec{v}$ is the velocity vector of the particle in the rotating system, and $\vec{\omega}$ is the angular velocity vector of the rotating vector (which has magnitude equal to the rotation rate and is directed along the axis of rotation).

$$\vec{F}_c = -2m\vec{\omega}\times\vec{v} \qquad \text{……………………………………………………………………..…} \quad (6)$$

Where $\vec{F}_c$ is Coriolis force acting on the particle and m is mass of the particle.

For example in the general arrangement of a meter of U-tube configuration shown in **Fig. 2.1**, the electromagnetic driver causes the tube to perform an oscillatory rotation about the y-axis. Fluid flows in opposite directions in the straight limbs of the U-tube so the effect of the Coriolis acceleration is to cause an oscillatory twisting of the tube about the x-axis. This secondary motion is exceedingly small compared with the main vibration about the y axis but it causes a slight difference in the phase of the signals from the detectors. The total mass flow of the fluid can be deduced from the measurement of this phase difference.

The physical principle used to determine process fluid density is similar to that used in vibrating tube density meters. In Coriolis meter the measuring tube conveying the process fluid, is driven to oscillate and its resonant frequency is determined. The amount by which resonant frequency obtained in presence of process fluid is shifted from that obtained *in vacuo* is a function of the density of the process fluid, which can then be determined.

A feedback circuit is used to maintain the vibration, an amplified form of the signal received at one detector being used to power the drive. The rectified signal from one detector is employed as a gain control for the driving voltage. In this way the amplitude of vibration at the fundamental frequency is maintained at a fixed level. Since losses are small the fundamental natural vibration motion is effectively set up and maintained.

A single straight tube Coriolis meter was used in the experiment (**Fig. 2.2**). Its operation is similar to U-tube design explained above.

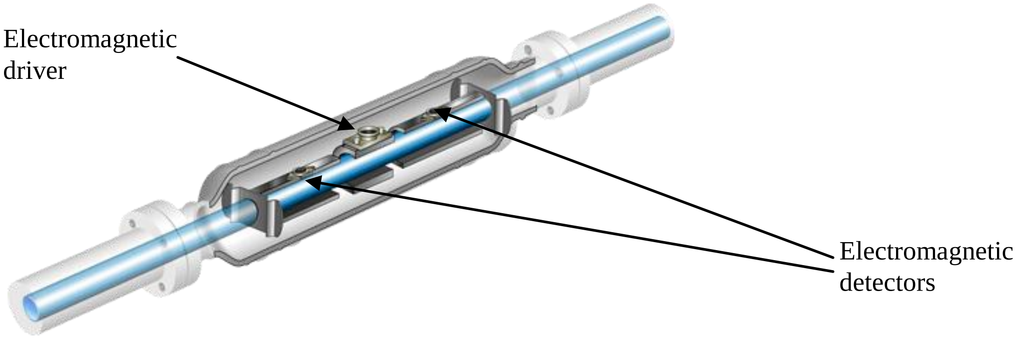


**Fig. 2.2 – Single straight tube Coriolis meter**.

## 2.3 Performance and applications

Coriolis massflow meters have emerged as the fastest growing fluid metering technology over the past decade. With worldwide revenues presently greater than $400 million and moving to $600 million in near future, Coriolis technology is considered as market leader mass flow metering technology by many. A major reason for this phenomenal growth is its ability to measure single phase fluids with accuracy and repeatability of 0.2% or less; which without question makes it the most accurate general purpose meter used by industry. It has been used successfully in wet-gas with at most 2.5% of liquid. It has been used successfully for many applications including, but not limited to the following:

- Custody transfer and fiscal metering of industrial gases (e.g. Carbon dioxide, Nitrogen) and natural gases.
- Custody transfer and fiscal metering of crude oil and other natural liquids.
- Metering of liquid-liquid emulsions.
- ‘Check’ metering of natural and industrial gases.
- Batch and continuous reactor feed.
- Process control of combustion gases (e.g. natural gas feed to reactors).
- Process control of cryogenic fluids (e.g. Nitrogen, Argon, Oxygen).
- Measurement of highly corrosive acids, bases and liquid-solid slurries (e.g. water-hydrate slurry).
- Interface detection.

**Fig. 2.3 – U-tube Coriolis meter in use for calibration of other meters at CEESI, Colorado**.

Apart from being very accurate, Coriolis technology has several other advantages; some of them are:

- It is not affected by the thermodynamic state of the fluid (i.e. temperature, pressure or density of measured fluid to a large extent).
- They are fairly independent of the rheological properties of the fluid; this makes it quite suitable for Newtonian and non-Newtonian emulsions. This being said, Coriolis meters are affected by density of fluid, though dependence is not as much as seen in some other metering technologies.

- They are almost non-intrusive in nature; though some pressure drop does occur in the vibrating tube.
- They can measure massflow rate directly. Most of the other meters measure volume flow rate, which is dependent on thermodynamic (pressure, temperature) state of fluid. Mass measurement, therefore is considered superior.
- Capital savings because of relatively short installation length requirement and easy retrofit.
- Bi-directional flow capability; not many designs allow this but it is theoretically possible.
- Less secondary instrumentation is required. It measures both massflow rate and density, thus compared to traditional metering technologies (e.g. turbine meter, orifice meter) fewer pressure transmitters are required.
- Broader flow ranges possible; generally ratio between lowest and highest flow rates is 1:100.
- Operational savings because of the on-board diagnostic capabilities.

## 2.4 Limitations of Coriolis meters

Coriolis technology, like all other metering technologies has few disadvantages associated, which limit the use of it. One of the limitations is high CAPEX of the meters and associated circuitry. At present generally cost of Coriolis meter is more than orifice meter and turbine meter, but is definitely less than metering technologies like gamma ray and sonar. This cost is expected to come down as more meters are installed worldwide.

Another major limitation of Coriolis meter is its inability to handle aerated liquids or wet gas with reasonable accuracy. Coriolis meter by design is a single phase meter. Multiphase flow through a Coriolis meter becomes a very complicated fluid-structure problem. Though Coriolis meter by design works in multiphase flow but past works show that the errors in mass flow rate and density reading can be as much as 80% even with low presence of secondary phase; also as the gas volume fraction in aerated liquids rise, so does the power required by the driving circuitry. There have been attempts to remedy this limitation by improving analog and digital circuitry, but with limited success. This work attempts to investigate the multiphase flow envelope, straight tube Coriolis meter can work in with reasonable accuracy. Also effects of flow conditioning on this envelope will be investigated.

# CHAPTER III

# EXPERIMENTAL PROGRAM

## 3.1 Test facility

The experimental two-phase flow loop consists of a pumping and metering section where required flowrates of individual phases are controlled and metered, and straight tube Coriolis section where most of experimental data is acquired (**Fig. 3.1**). Coriolis section itself is set-up in inlet section and actual straight tube Coriolis meter. A separate inlet section provides the flexibility of installing different flow conditioners upstream of Coriolis meter and observing their effect on the Coriolis performance.

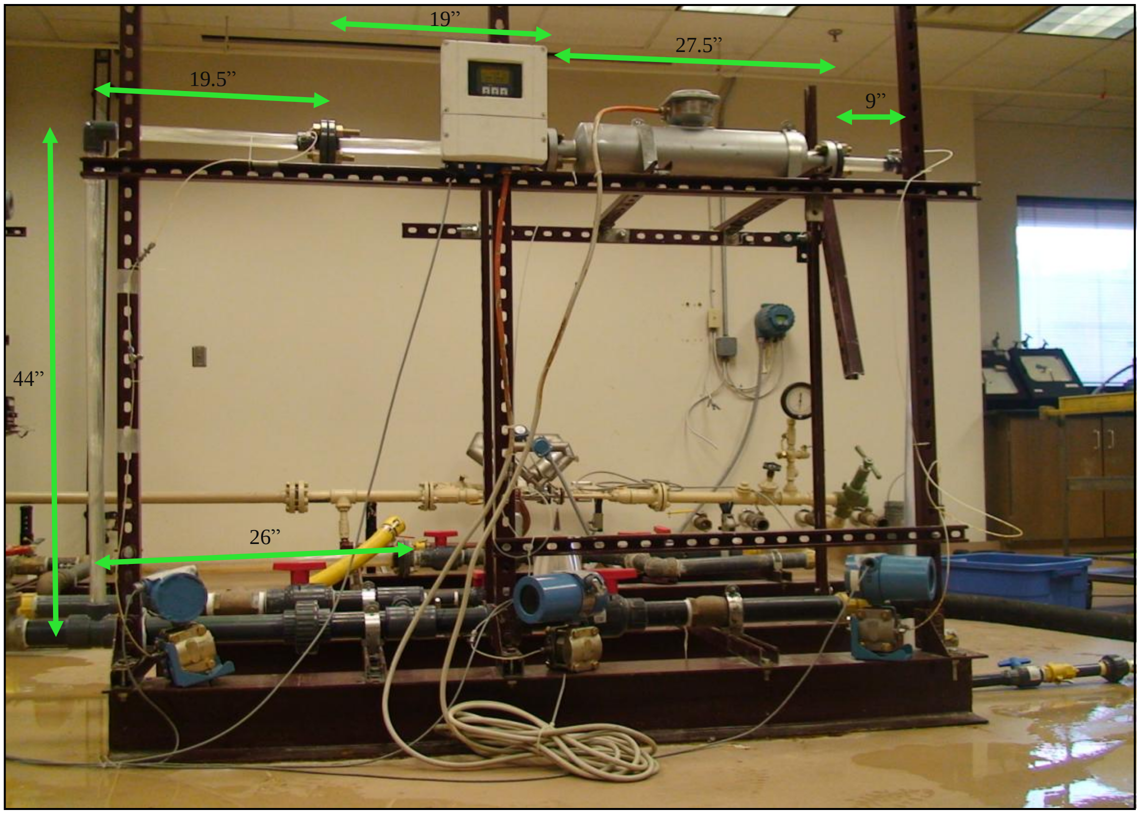


**Fig. 3.1 – Experiment flow loop**.

### 3.1.1 Coriolis meter test section

The test section consists of straight tube Coriolis meter (**Fig. 3.2**). The meter is a single straight tube design from Endress & Hauser; nominal diameter of the fluid conveying tube is 1 inch. Vendor stated range of mass flowrates through the meter is from 0 to 660 lb/min. The test section is divided into three primary parts:

- Phase mixing section.
- An inlet section adaptable to various flow conditioners.
- A single straight tube Coriolis meter.

**Fig. 3.2 – Single straight tube Coriolis meter used in experiments**.

### 3.1.2 Inlet section

Inlet section is made by transparent 1 inch PVC pipe and is compartmentalized in primary test section by means of flanges. This makes it adaptable to different flow conditioners used in the experiment by reducing the time and effort needed to change the configurations. Two types of flow conditioners were used in the experiments:

- Swirl generator: It acts as a phase segregator (**Fig. 3.3**). A flow of multiphase mixture through the swirl generator causes the heavier phase to flow on the periphery of the tube with the lighter phase occupying the middle of the tube. This is caused by the centrifugal forces generated as the fluid rotates in transit through the swirl generator. Hardware similar has been used in past to separate two phase mixtures[27].

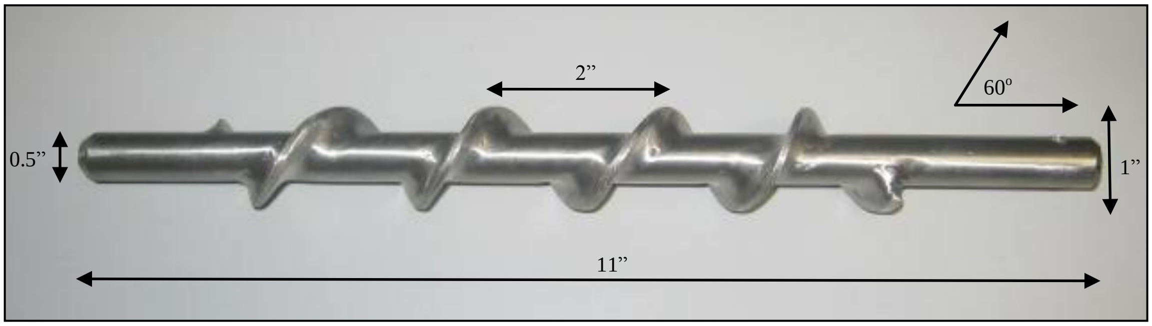


**Fig. 3.3 – Inlet swirl generator**.

- In-line mixer: It acts as a phase homogenizer. The model used in the testing is Ryan Herco all plastic static in-line mixer (6 elements) with nominal diameter of 1 inch. (**Fig. 3.4**). Multiphase flow through the mixer comes out as a well homogenized mixture of phases with the slip velocity between the phases minimum. This occurs due to various obstructions (built in the mixer) encountered by the flow. The pressure drop along the obstructions act to break the secondary phase into small droplets dispersed throughout the primary phase. This makes the mixture "homogeneous" in a macroscopic sense.

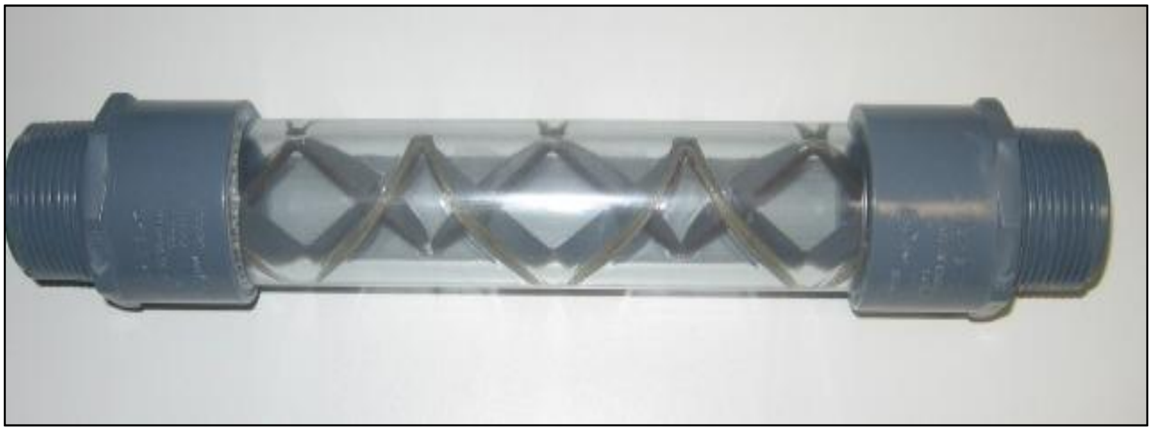


**Fig. 3.4 – In-line mixer**.

**Fig. 3.5 – Aerated liquid flow without flow conditioners**.

Visual inspection during the tests has been done during the tests to confirm the effects of flow conditioners. **Fig. 3.5** shows the aerated flow in the tube with no flow conditioners; as visible there is significant inhomogeniety present in the phase with air bubbles majorly present in the top of the tube. Inlet swirl generates a concentric core of air as seen in **Fig. 3.6**. The swirl continues throughout the meter length (**Fig. 3.7**).

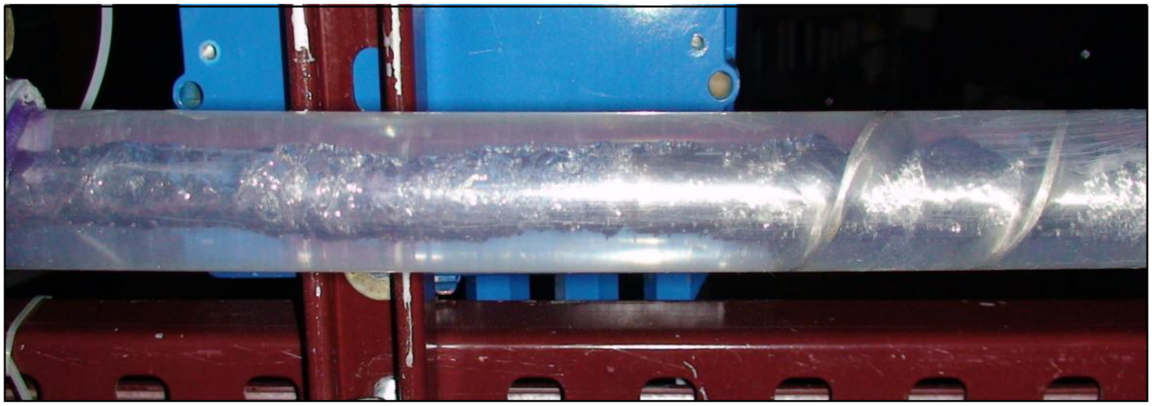


**Fig. 3.6 – Aerated liquid flow in presence of inlet swirl**.

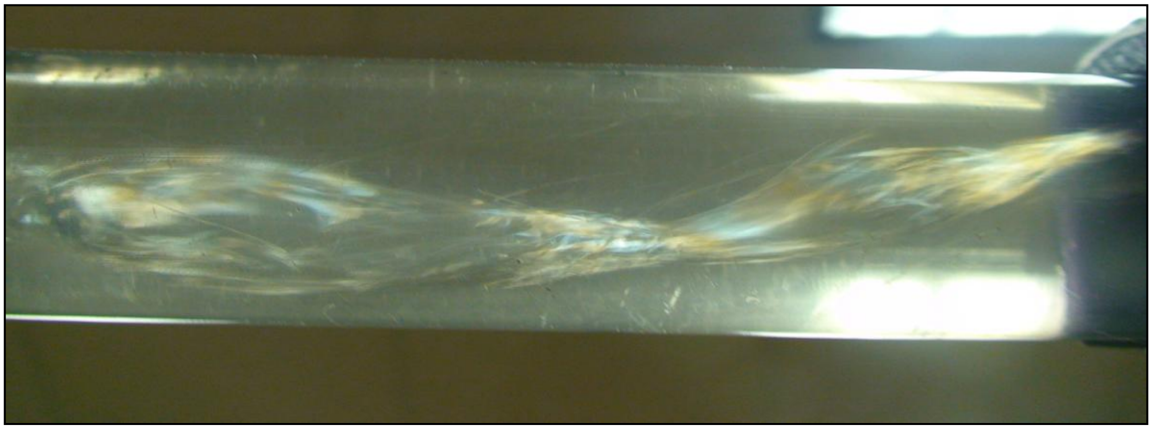


**Fig. 3.7 – Snapshot of aerated liquid flow exiting the Coriolis; it confirms that swirl continues throughout the meter**.

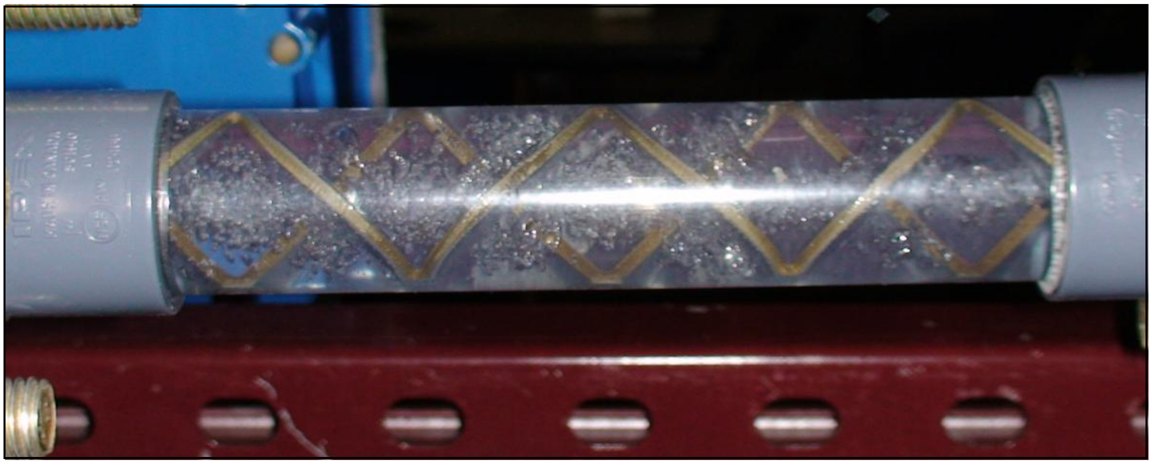


**Fig. 3.8 – Inline mixer in aerated liquid flow**.

**Fig. 3.8** shows the inline mixer in aerated liquids. It tends to create and disperse large amounts of smaller air bubbles (**Fig. 3.9**) and thus makes the flow "homogenized".

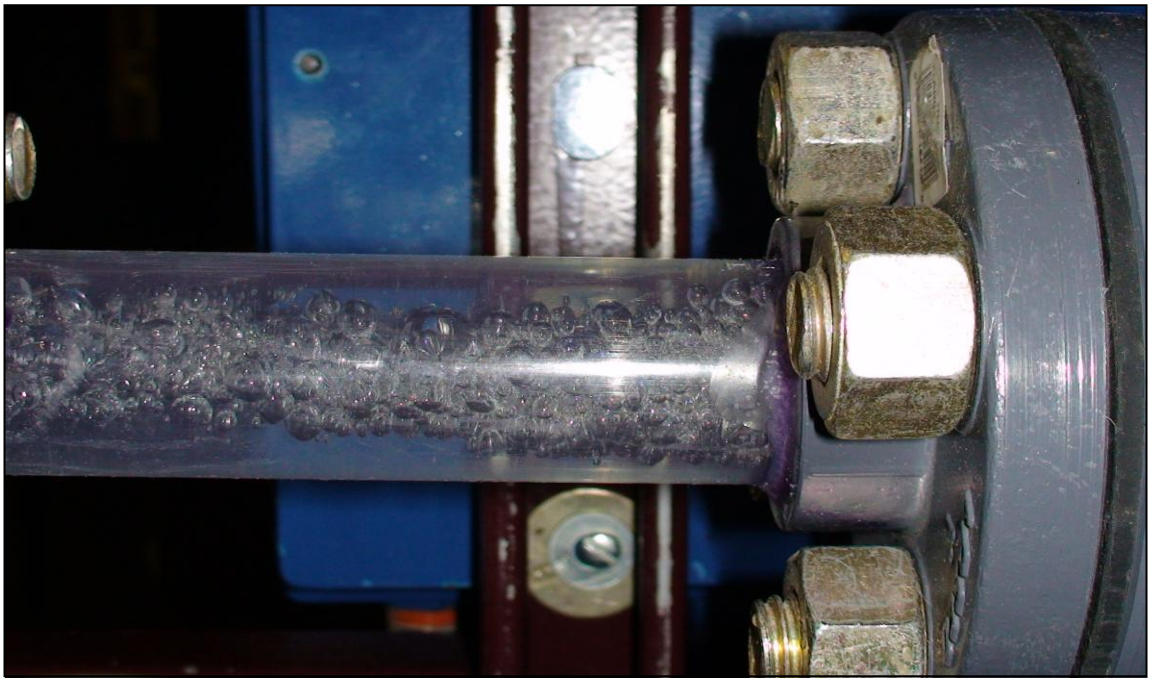


**Fig. 3.9 – Inline mixer creates large amounts of smaller bubbles**.

### 3.1.3 Metering section

The metering section consists of two parallel, single-phase feeder lines for measuring individual incoming single-phase gas and liquid flow rates. Air, which is supplied by an air compressor, is used as the gas phase in the present setup. The air flow rate into the loop is controlled by a regulating valve and metered by an elite series Micromotion (ESM) Coriolis meter. The liquid phase used in the current work is water. It is supplied from a 15-barrel storage tank at atmospheric pressure and pumped to the liquid feeder line by a combination of two centrifugal pumps. Variable frequency drives are used to control the drive frequency of centrifugal pumps; drive frequency controls the liquid flow rate.

Similar to the gas phase, the liquid flow rate is metered using 1½-in. Model D Micromotion meter. The single-phase gas and liquid streams are combined at the mixing tee and delivered to the test section. No-return valves, located downstream of each feeder, are installed to prevent backflow. The two-phase mixture downstream of the test section is separated by a conventional separator. The air is vented to the atmosphere and the liquid is returned to the storage tank to complete the cycle.

### 3.1.4 Uncertainty analysis

Uncertainty analysis is performed on single phase tests to determine level of confidence in the results. Vendor provided technical manuals[25,26] are used to get accuracy information about participating instruments. Relevant information used to calculate uncertainties of measured parameters are presented below:

- Mass flow rate of liquid: maximum uncertainty of $\pm 0.1\%$ of rate.
- Mass flow rate of gas: maximum uncertainty of $\pm 0.5\%$ of rate.
- Density measurement of liquids: maximum uncertainty of $\pm 0.5$ kg/m$^3 \approx \pm 0.0312$ lb/ft$^3$.
- Temperature measurement of gas: maximum uncertainty of $\pm 1^0\text{C} \pm 0.5\%$ of reading in $^0$C $\approx$ 69.6 $^0$F to 73.6 $^0$F (test temperature is constant at 72 $^0$F).
- Pressure measurement: 0.25% of the range of the transducer (100 psi in this work).

Expressions resulting from these considerations are used to calculate uncertainty associated with reference measurements and presented as range of errors (of mass flow rate and density readings for single phase flows) in chapter IV.

$$MFR_{l,actual} = MFR_{l,observed} \times (1 \pm 0.001) \quad \text{…………………………………………….. (7)}$$

$$MFR_{g,actual.} = MFR_{g,observed} \times (1 \pm 0.005) \quad \text{……………………………………………. (8)}$$

$$\rho_{l,actual} = \rho_{l,observed} \pm 0.0312 \quad \text{……………………………………………………... (9)}$$

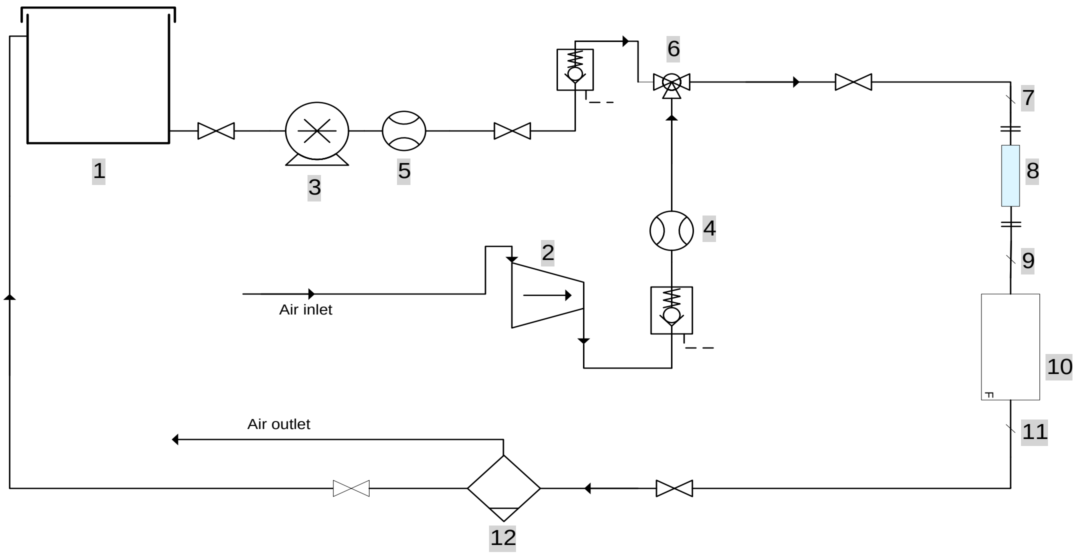
And for density of air, applying ideal gas law at the inlet of the Coriolis meter,

$$\rho_{a,actual} = \frac{P_{inlet,actual}}{RT_{actual}} = \frac{P_{inlet,observed} \times (1 \pm 0.0025)}{R \times (71.6 \pm 2)} \quad \text{…………………………………... (10)}$$

An important assumption made during uncertainty analysis is that variables measurements are considered independent of each other, i.e. density reading of liquid is not affected by mass flow rate reading of the Coriolis meter. Results of uncertainty analysis are presented in Chapter IV.

## 3.2 Experimental procedure

The overall test schematics used for this experimental work appears in **Fig. 3.10**. Air, and water run in the flow loop; Water is pumped into the loop from water storage tank by centrifugal pumps.



1 – Water/Oil storage tank

2 – Air compressor

3 – Centrifugal pumps

4 – Air meter (1)

5 – Liquid meter (2)

6 – Mixing tee

7 – Pressure transducer before flow Conditioner (1)

8 – Flow conditioner (inlet swirl/inline mixer)

9 – Pressure transducer after flow conditioner (2)

10 – Straight tube Coriolis meter

11 – Pressure transducer after Coriolis meter (3)

12 – Separator

**Fig. 3.10 – Process Flow diagram of experimental setup**.

Variable frequency drives are applied to control liquid flow rates. Air for the gas loop comes from a compressor, which is regulated with a needle control valve. Pressure transducers are located all around the test facility to provide the required pressure measurements. Mixing tee is used to mix the two single phase streams into a single two-phase flow, it is shown in **Fig. 3.11**; 0.5 inch pipe is used to inject secondary phase into 2 inch pipe carrying primary phase. An additional needle valve on the 0.5 inch flow line provides additional control on secondary phase flowrates. After passing through the test section, multiphase flow is allowed to flow back to a settling tank (separator), where air is released to the atmosphere and liquid is recirculated.

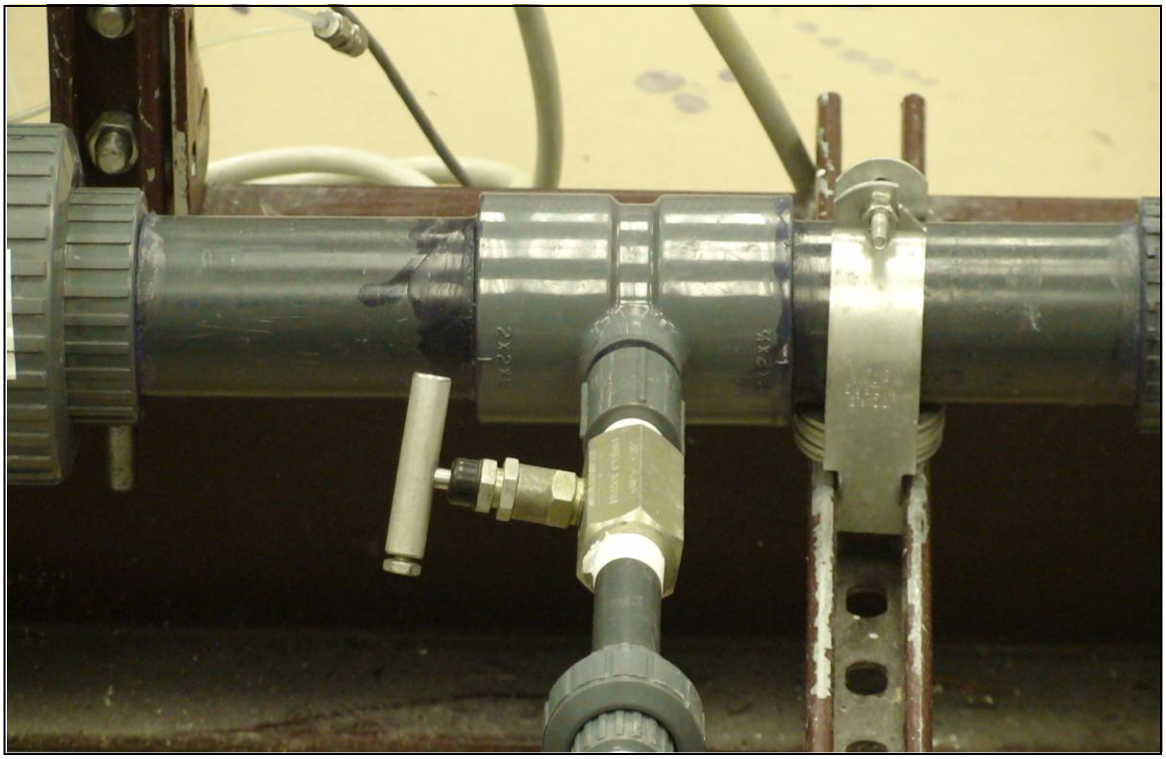


**Fig. 3.11 – Mixing junction. Secondary phase is injected through ½'' pipe in primary phase being carried through 2'' pipe**.

### 3.2.1 Data acquisition system

To monitor real time behavior of the experiments, it is essential to record various parameters that define the process. Apart from the flowrates, pressure and temperature at various points are important parameters. Air temperature is given as additional output by ½ inch Coriolis meter used to measure air flow rates.

Three Rosemount (Emerson) absolute pressure transducers are installed on the flow loop. They measure pressure readings before inlet section, after inlet section and after Coriolis test meter respectively, and transmit a proportional or square root (flow) electrical signal. The differential pressure gauges are energized by a 20 volts single DC power supply and output 4~20 mA DC current signals that travel to hardware via grade 16AWG electric cable.

The connections of the transmitters are assembled with 1/8" hastelloy C276 tubing and GYROLOK compression fitting. **Fig. 3.12** shows the connection mode to capture the electric signals and convert to PC based data acquisition system.

The NI CB-68LP board is the device that receives the electric signal from the transducers, via the wires, and transfers the signals to the main board inside the computer; see **Fig. 3.13**. It has a direct network interface, processes I/O signals on up to 64 channels, eight of which are type analog. The channels entering to the board and its distribution and recognition are programmed by the software LabVIEW from National Instruments.

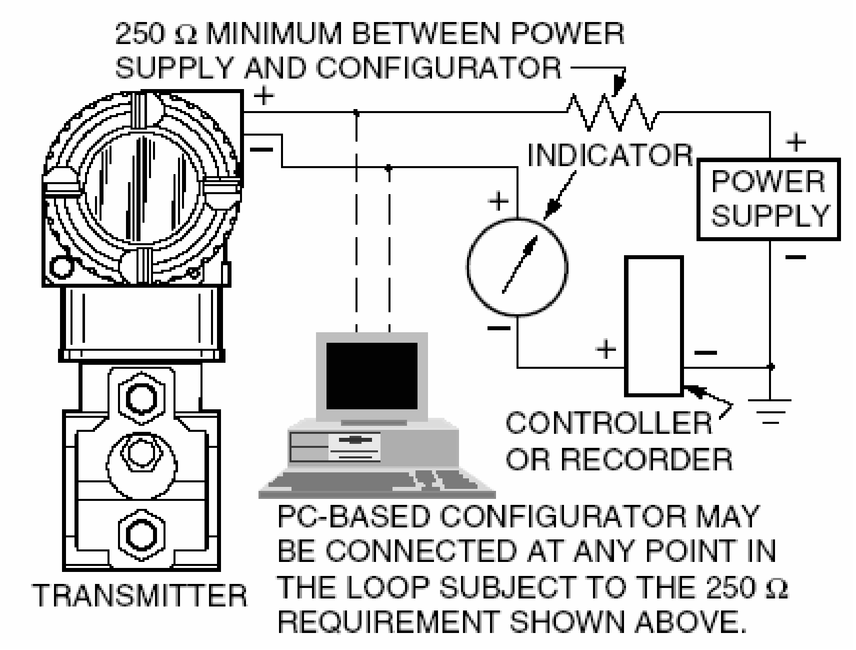


**Fig. 3.12 – Schematic of pressure signal acquisition**.

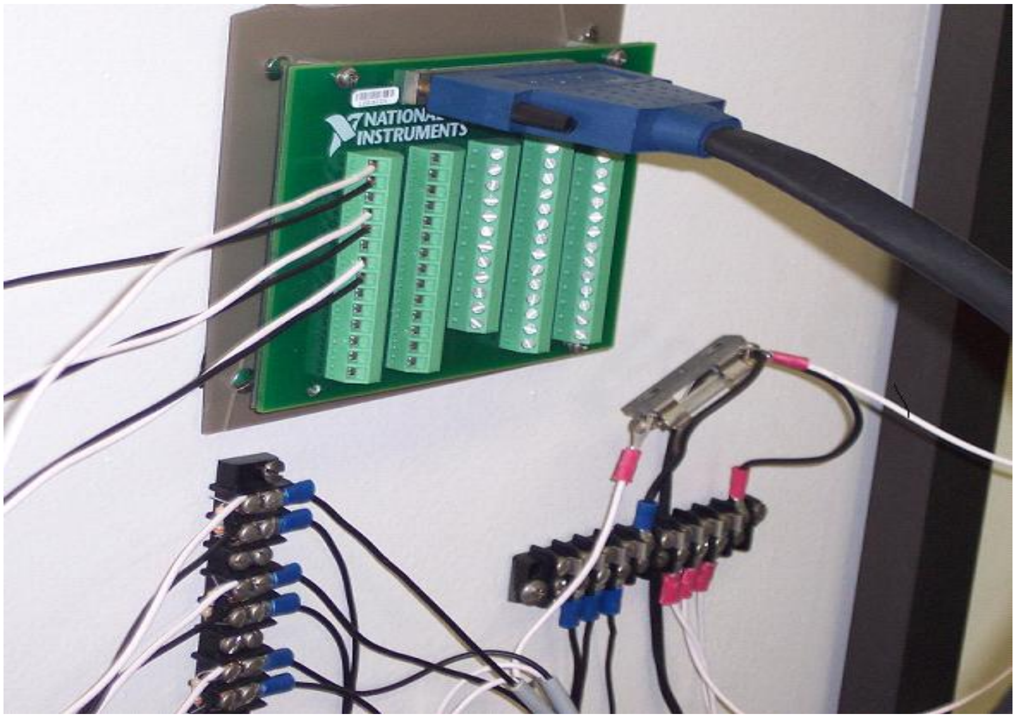
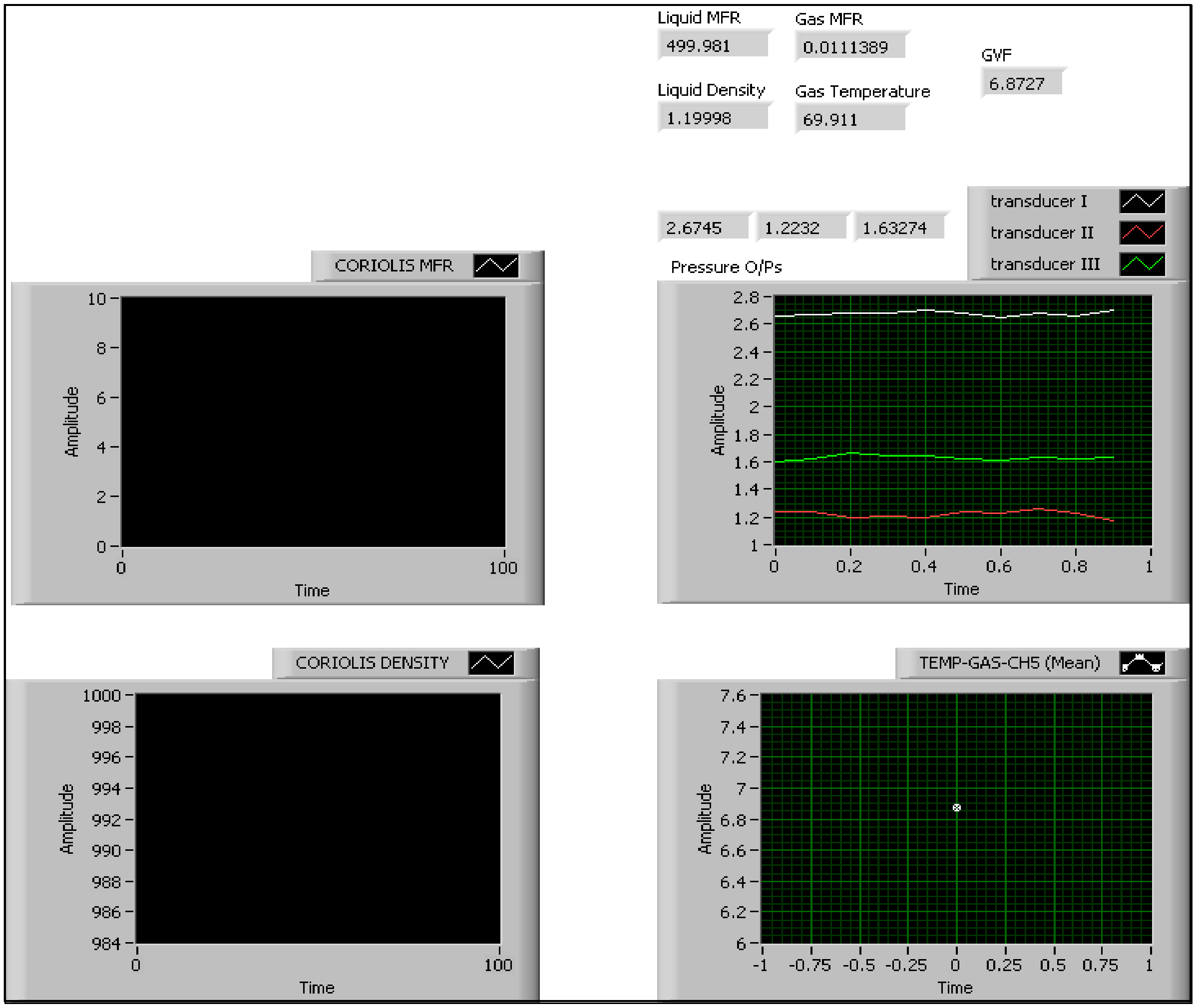


**Fig. 3.13 – NI Interface Board CB-68LP DAQ**.

The three pressure signals use independent analog channels in the interface board; these signals are then distributed and directed to the main board installed inside desktop. These three signals are processed by the software LabVIEW which automatically recognizes and display them on a wave chart in front panel as shown in **Fig. 3.14**.



Liquid MFR 499.981

Gas MFR 0.0111389

GVF 6.8727

Liquid Density 1.19998

Gas Temperature 69.911

Pressure O/Ps 2.6745 1.2232 1.63274

**Fig. 3.14 – Data acquisition LabVIEW program (front panel)**.

The software works with specific commands for each tasks and it easily links the pressure signals with the workflow to calculate the GVF encountered by the test Coriolis meter. Finally the pressure and GVF readings along with flowrates of both water and air are sent to be written in a file. The sampling frequency is fixed at 10 Hz .When a steady state condition is attained; a mean of data recorded for a run, usually about 5 minutes is taken as the final measurement. The file can be extracted as a excel spread sheet to represent the differential pressure and permeability data. **Fig. 3.15** shows the block diagram of the LabVIEW with the program to acquiring and writing the data.

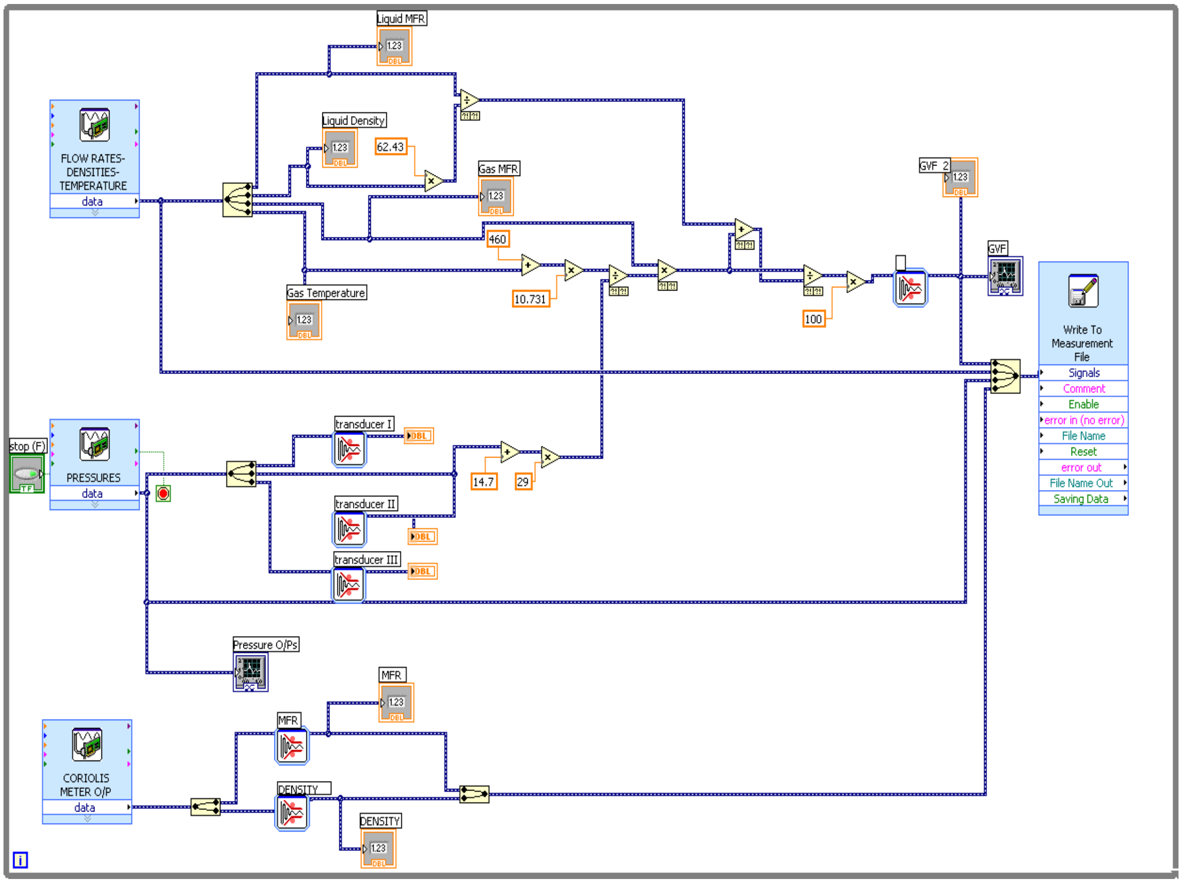


**Fig. 3.15 – Data acquisition LabVIEW program (block diagram)**.

### 3.2.2 Single phase test procedure

Single experimental setup is used for conducting both single phase and two-phase tests. In single phase tests, both air and water are allowed to flow through the test skid individually. This is done by cutting off secondary phase flow by means of control valves. Single phase tests were performed both with and without flow conditioners. The meter was tested for both air and water. Upper limit of flowrates for which meter was tested were limited due to incapability of clear PVC pipe (used in the experiment for visual inspection) to handle high pressures. Frequency of swirl in single phase flows can be easily determined; another interesting testing can be to measure the output of the meter as the swirl frequency nears the frequency of the meter itself, and to see what happens when those two are same. When these two frequencies will be same, resonance will occur, but that is very hard to achieve since commercial coriolis meters vibrate at 100 hertz to 200 hertz. This effect has not been discussed in present work.

### 3.2.3 Two phase test procedure

Two scenarios are given emphasis while testing flow-loop for two phase flows:

- Aerated liquids: Aerated liquids are generated by introducing trace amounts of gas in liquid flow. Amount of air in liquid is varied to observe the change in Coriolis performance. Tests are carried out till the gas volume fraction above which the error in mass flow rate becomes more than 10%. Tests are done without using flow conditioners, as well as with swirl generator/in-line mixer.

- Wet gas: Trace amounts of liquid are introduced in the gas stream to generate wet gas flows. As in aerated liquid testing, here too amount of liquid present in the flow is varied to observe the effect of change of liquid loading on Coriolis performance. This also gives an operation envelope, where Coriolis meter can work with reasonable accuracy, in spite of being subjected to two phase flow. As before, tests are carried out in presence of flow conditioners as well as without them.

# CHAPTER IV

# SINGLE PHASE METERING WITH CORIOLIS METER

Previous literature shows that Coriolis meter works best in single phase flows. First step in this work is to test the meter in single phase flows to ascertain the performance of the meter at different flowrates. This step can be viewed as a pre calibration procedure. Single phase testing was done for both air and water flows. Also, effect of flow conditioning is determined by employing both inlet swirl and inline mixer just before the inlet to the Coriolis. Following sections describe the results obtained during the testing.

## 4.1 Single phase water tests

Tests were done using water as the singular phase while keeping the air supply closed. Using the centrifugal pumps water was pumped at different rates and the corresponding mass flowrate and density readings of test meter were acquired using data acquisition system. Reading reported are mean of several reading taken over an interval of 5 to 10 minutes when steady state conditions prevailed. **Fig. 4.1** and **Fig. 4.2** show the data captured during the tests. From these plots, flow conditioning has no or minimal effect on the mass flowrate and density readings of the Coriolis meter in case of single phase liquid flow. These results suggest that the metering technology is immune to velocity vectors associated with the fluid being metered in above mentioned conditions. This has important implications for practical use of this technology. Flow conditioning is not essential for accurate metering of the fluid. This also eliminates the need to install a straight length of pipe between the meter and any sort of bend or elbow.

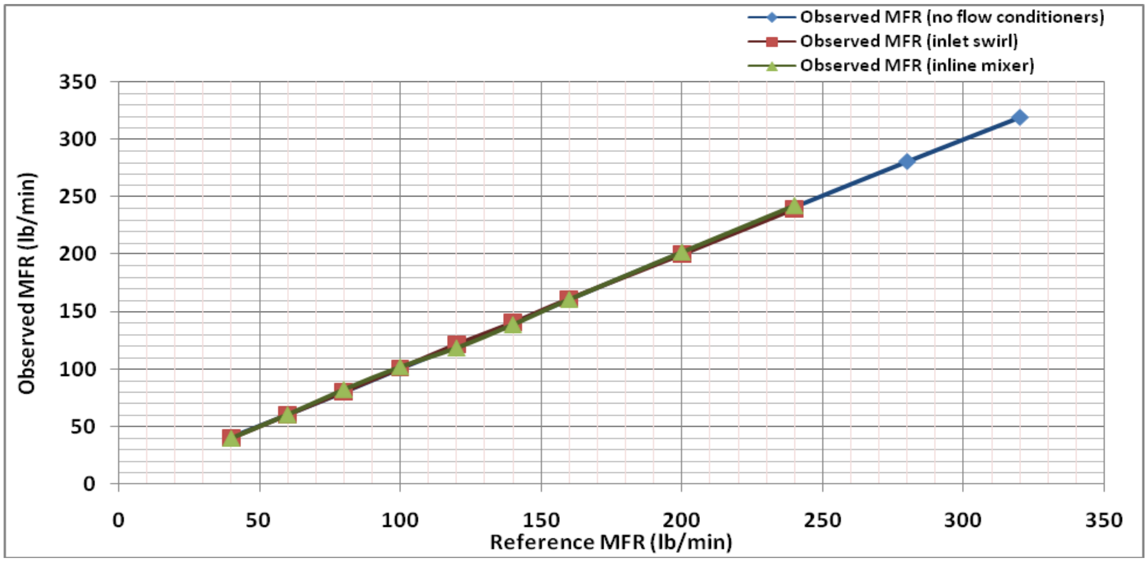


**Fig. 4.1 – Effect of flow conditioners on MFR reading in single phase liquid test**.

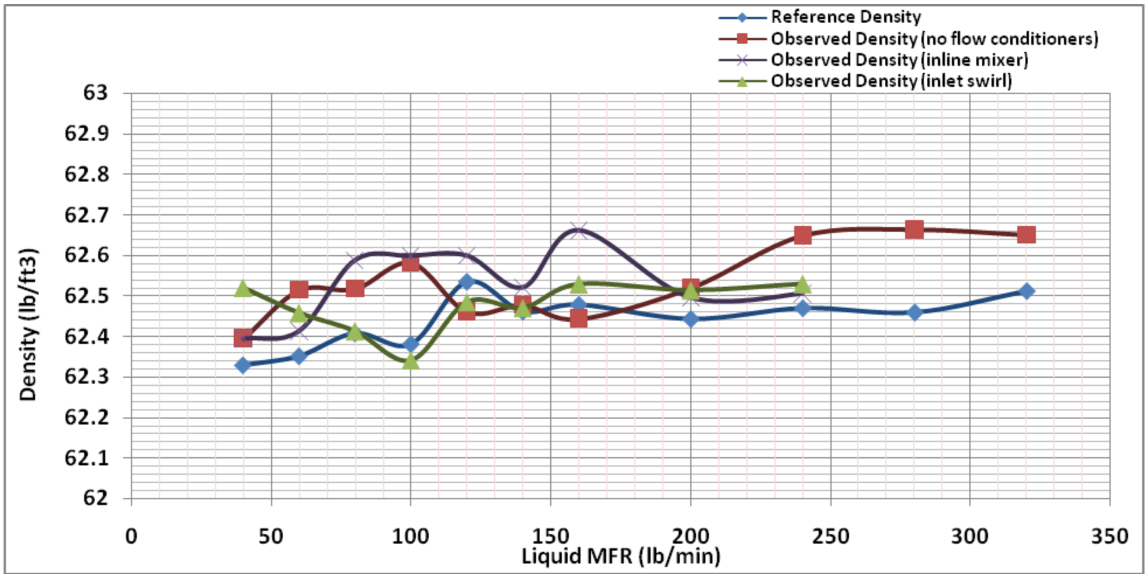


**Fig. 4.2 – Effect of flow conditioners on density reading in single phase liquid test**.

Errors recorded in the experiments along with range of uncertainty in reference measurement are plotted versus liquid mass flow rates in **Fig. 4.3** and **Fig. 4.4**, for liquid mass flow rate and liquid density respectively.

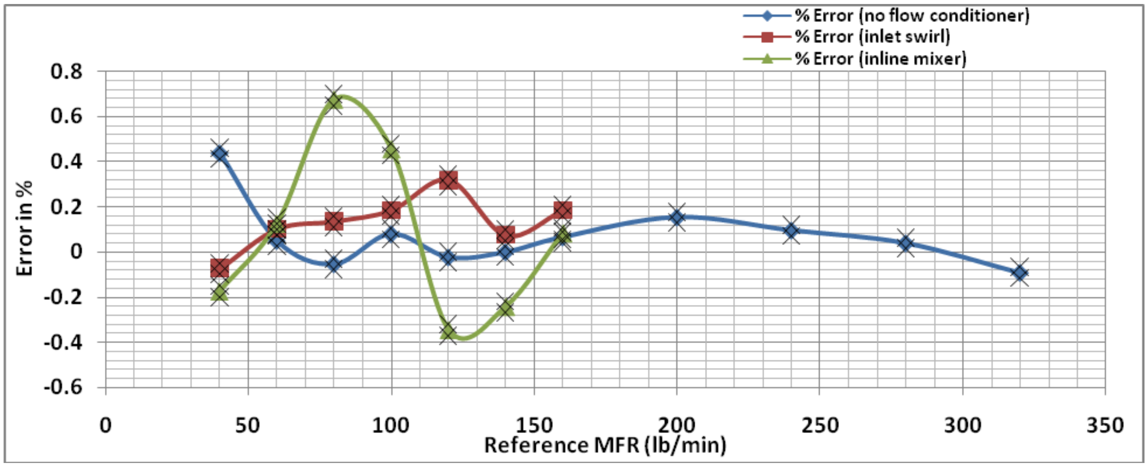


**Fig. 4.3 – Error in liquid mass flowrate with range of uncertainty (black markers)**.

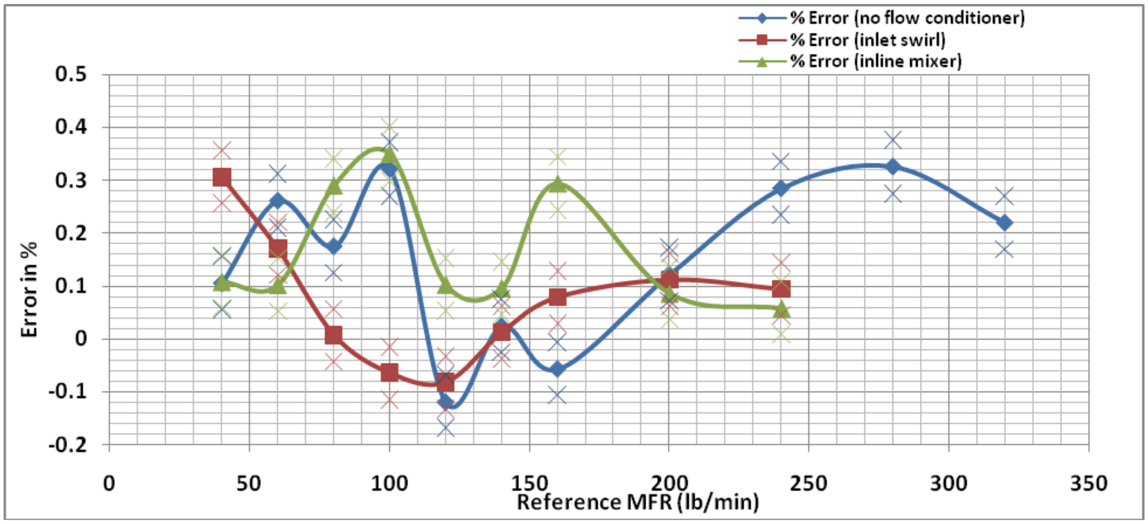


**Fig. 4.4 – Error in liquid density with range of uncertainty (same color)**.

As seen in the figures, error magnitudes are relatively small ($\sim\pm0.6\%$) for mass flow rate and ($\sim\pm0.3\%$) for liquid density. No clear trends are visible, and errors can be attributed random.

## 4.2 Single phase air tests

Single phase air tests are done in similar fashion as described in previous section, only during these tests water inlet remains closed. **Fig. 4.5** and **Fig. 4.6** show the data captured during the tests. Results show no or minimal effect of flow conditioning before the meter. This aspect is similar to the results described in previous section. This response of the meter in presence of any single phase flow could be attributed to the fact that the response of the meter to flow vectors is negligible to the order of force generated by high vibration frequency of the meter itself.

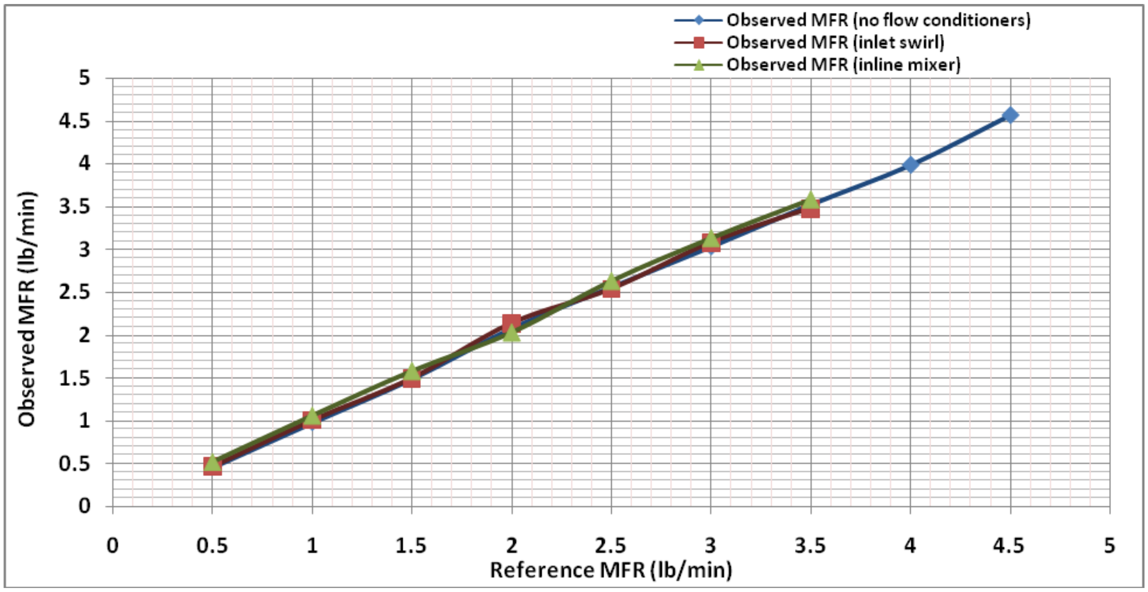


**Fig. 4.5 – Effect of flow conditioners on MFR reading in single phase air test**.

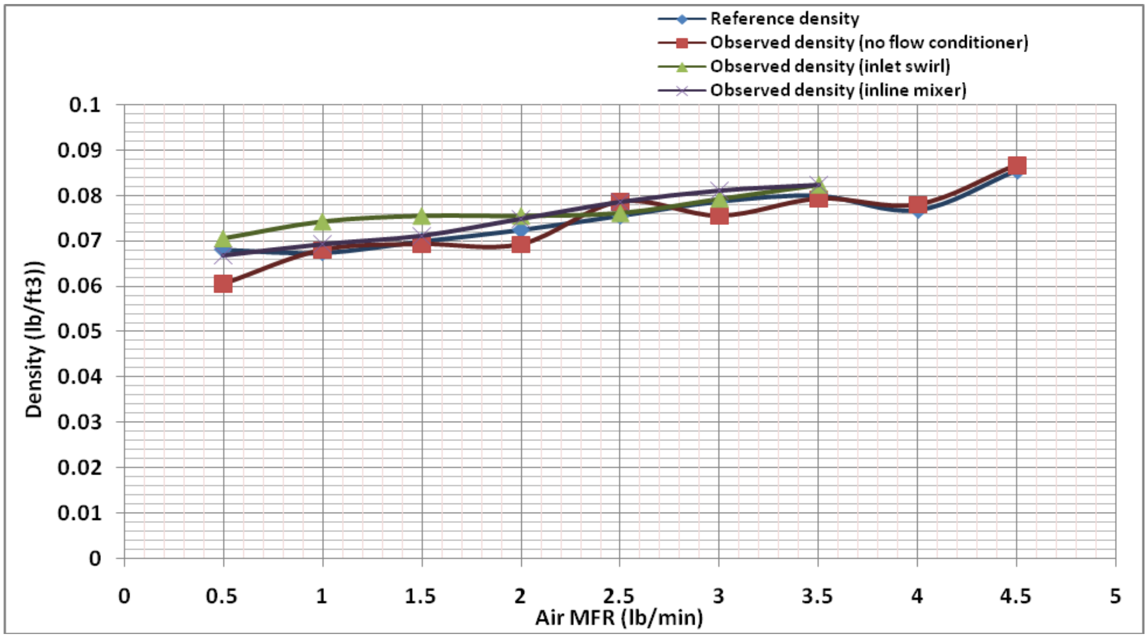


**Fig. 4.6 – Effect of flow conditioners on density reading in single phase air test**.

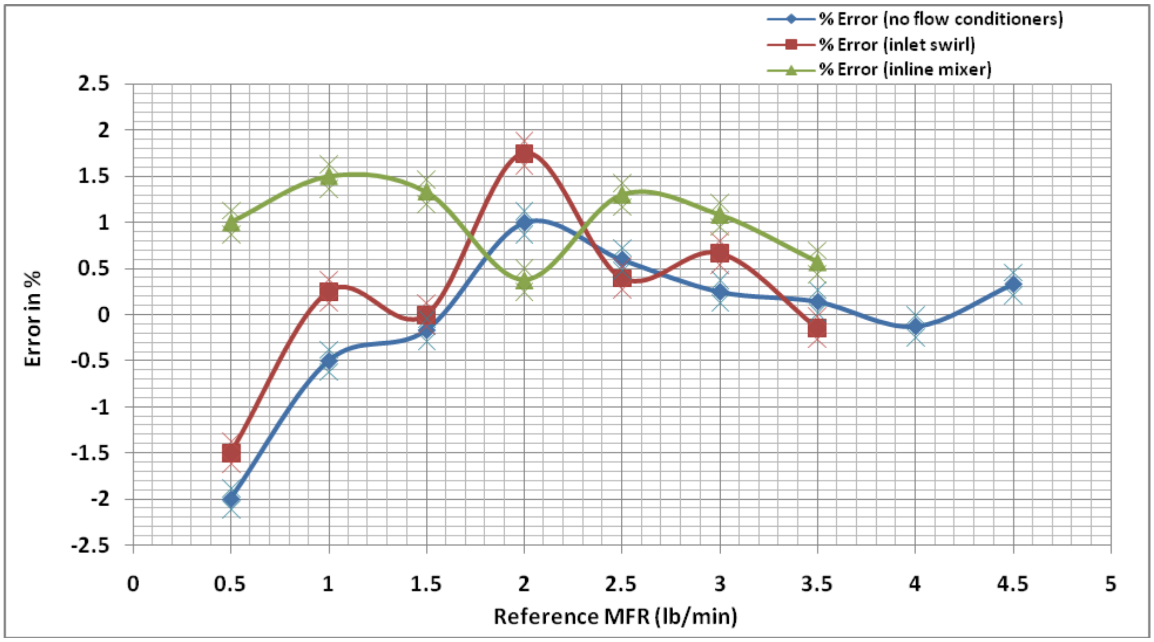


**Fig. 4.7 – Error in air mass flow rate with range of uncertainty (same color)**.

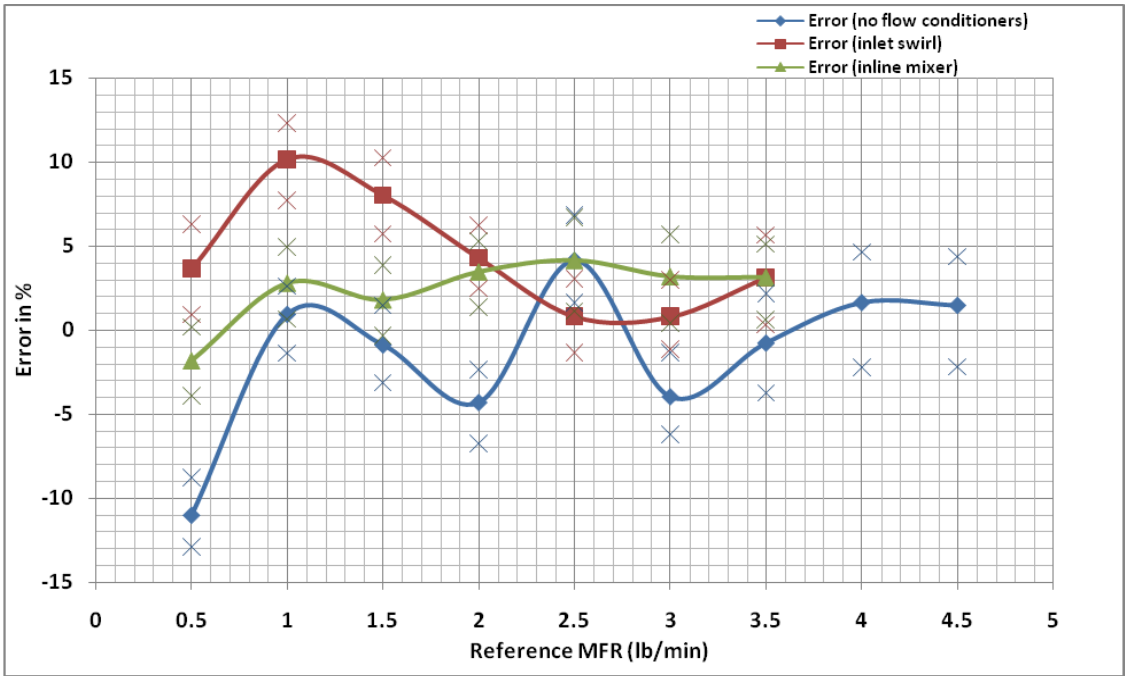


**Fig. 4.8 – Error in air density with range of uncertainty (same color)**.

**Fig. 4.7** and **Fig. 4.8** shows the relative difference between the reference (actual) and the bserved parameters for mass flow rate and density respectively, along with the renge of uncertainty in reference air mass flow rate and uncertainty in calculation of reference density respectively. Though error magnitude in air mass flow rates are small (~±2%), it is larger than in case of liquids. Errors in air density readings are very significant (~±10%). The reason for these observations seems to be the inability of coriolis meter to handle low density fluids at very low pressures; though this effect is more important in density readings than mass flow rate readings. Another observation is the reduction of error magnitude as the mass flow rates and hence the pressure is increased.

# CHAPTER V

# TWO PHASE METERING WITH CORIOLIS METER

An accurate and real-time measurement of multiphase flows composed of oil, water and gas phases is of great importance in many industries, such as chemical and process industries, oil refineries and particularly in exploration and production of crude oil and natural gas. A typical flow in any exploration and production operation consists of any combination of oil, water and gas. Traditionally metering has involved separation of these mixed flows into involved phases and using single phase meters to measure them. This is not only an expensive “brute force” method; it also has a large footprint, which in case of offshore operations is a hefty premium. As the drive towards attaining cost reduction and smaller foot prints, especially in offshore exploration and production operations gains momentum, the industry is searching for compact and inexpensive alternatives to the traditional “separate and measure” approach.

Though intense efforts are being done to come up with universal multiphase meters, unfortunately the basic nature of multiphase flows makes it virtually impossible for anyone metering technology to measure any and every combination of phases accurately. Currently there are several multiphase measuring technologies with individual niches. Most of these technologies use multiple sensors to deduce individual flowrates and other properties. Most of these technologies have a smaller footprint, albeit not a cost advantage when compared to traditional approach to the problem.

Owing to very high accuracy of Coriolis meters operating in single phase flows, it shows promise in emerging as a multiphase technology.

Coriolis meters have been evaluated in the past to measure two phase flows, as cited in literature review. At this point, it is still very difficult to develop a reliable theoretical model that can accurately predict behavior of Coriolis meter in two phase flows; this is evident by the fact that only bubble model has been widely used by researchers since late 90s till now[28]. This is because of the complex fluid-structure problem Coriolis meter poses operating in two phase flows; therefore, experimental investigation is needed to verify the performance and limitations of Coriolis meter in two phase flows.

Experimental program has been divided into two different types of two phase flows, namely aerated liquids and wet gas (**Fig. 5.1**); in the former flow primarily consists of liquid phase with small amounts of air, while in latter small volumes of liquid is introduced in air flow. Since these two phase flows differ widely from each other in their behavior, respective results are discussed separately.

In Fig. 5.1, test matrix is plotted on Taitel and Dukler flow regime map, created by FlowPat (Chevron) at atmospheric pressure and $72^0$ F. Axes of the map denote the velocity which each phase would be having in the coriolis meter if that phase alone was occupying the whole tube cross section. This is also termed as “superficial” velocity; hence the names of the axes are Vsl and Vsg, for superficial liquid velocity and superficial gas velocity respectively. It also shows the regions the data points lie; aerated liquids in dispersed bubble regime I and wet gas in annular flow regime A.

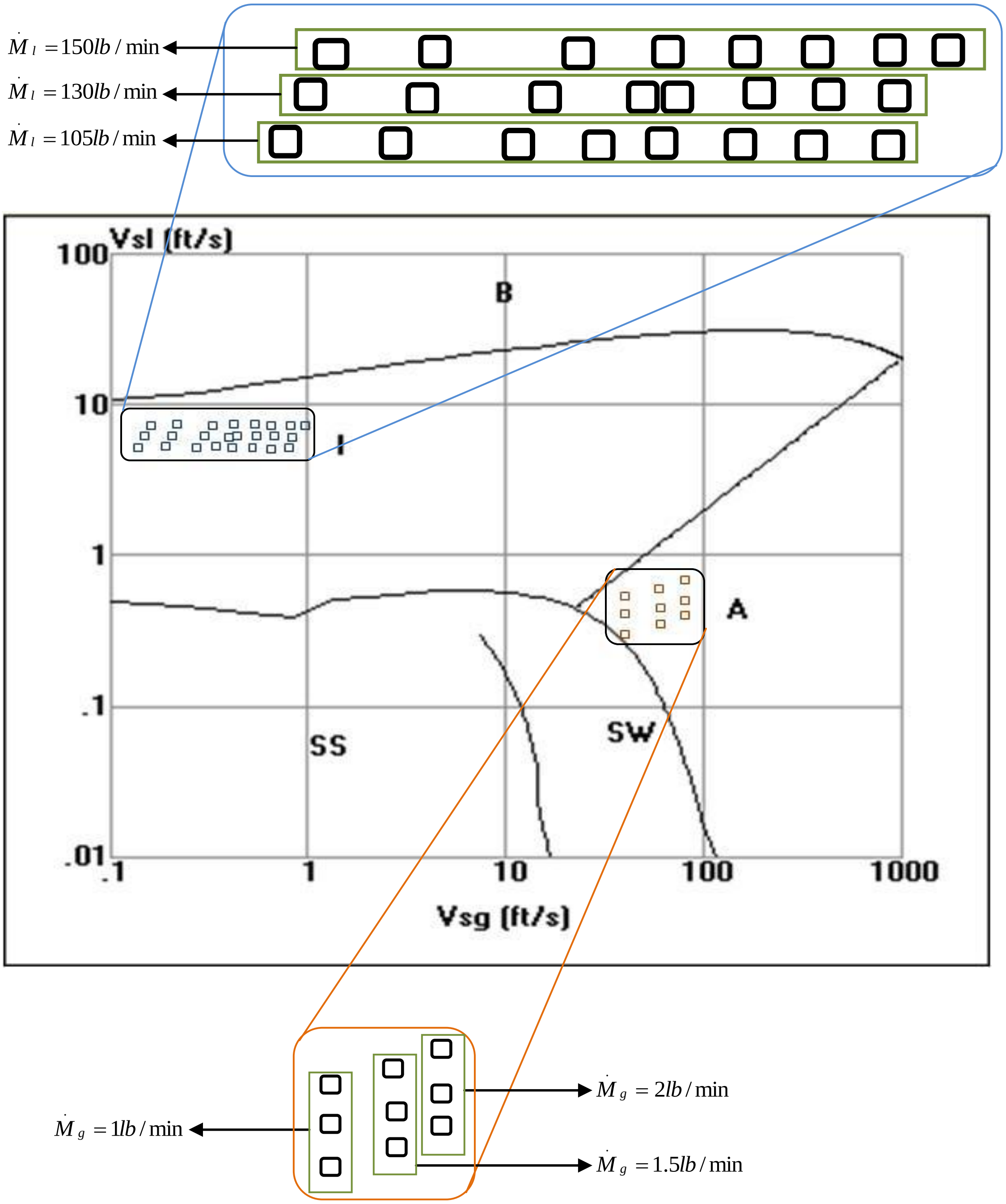


**Fig. 5.1 – Test matrix showing both aerated liquid (blue) and wet gas (orange) data points (plotted on Taitel & Dukler flow regime map at atmospheric pressure).**

Maximum pressure achieved before the Coriolis meter in these testing was 5 psig for cases with highest liquid mass flow rate and highest gas volume fractions; all the data points corresponded to pressures ranging from 2-5 psi, hence the flow pattern map was made for atmospheric pressure.

## 5.1 Aerated liquid tests

Aerated liquids are termed as flows containing primarily liquid with small amounts of gas. In actual field conditions this gas may come from reservoir or it may be dissolved in the liquid which comes out as “free” gas when considerable pressure drop occurs. In any practical field condition, it is nearly impossible to eliminate free gas from the liquid phase since any flow consists of pressure gradient; therefore it is imperative for meters to have certain resistance to liquid flows with small amount of air in them, even if it is supposed to operate in single phase flow. This is necessary to avoid a meter failure if conditions change and can be viewed as a contingency plan.

One of the aims of aerated liquid tests in current work is to observe whether the Coriolis meter can handle aerated liquid flows. The amount of gas present in the flow is quantified by gas volume fraction ($\alpha$), (also denoted by GVF) where,

$$\alpha = \frac{V_g}{V_l + V_g} \quad \text{……………………………………………………………………..} \quad (11)$$

V denotes the volume of a particular phase present in the flow, and l and g denote the liquid and gas phase respectively. GVF reported in results are calculated at the inlet of the meter by applying pressure correction to account for the expansion of the gas; this is due to drop in pressure between the supply air outlet and the Coriolis meter inlet.

As specified before in the metering subsection, air mass flowrate ($\dot{M}_g$) and temperature ($T_g$) are measured by the Coriolis meter installed on the air supply line, whereas liquid mass flowrate ($\dot{M}_l$) and liquid density ($\rho_l$) are measured by the Coriolis meter installed at the liquid supply. Since the experiment is conducted at ambient conditions, air is considered to be in isothermal conditions, which is confirmed later by direct measurements. Liquids are considered incompressible in all the experiments.

$$\dot{V}_l = \dot{M}_l / \rho_l \quad \text{……………………………………………………………………………. (11)}$$

$$\dot{V}_g = \frac{(T_g + 460) \times 10.7316}{(P_{inlet} + P_{atm}) \times 29} \times \dot{M}_g \quad \text{……………………………………………………….. (12)}$$

$$\alpha = \frac{\dot{V}_g}{\dot{V}_l + \dot{V}_g} \quad \text{……………………………………………………………………………. (13)}$$

Where $T_g$ is measured in Degree Fahrenheit, 10.7316 $\text{ft}^3$·psi·°$\text{R}^{-1}$·lb-$\text{mol}^{-1}$ is the universal gas constant, and 29 is the molecular mass of air. $P_{inlet}$ denotes the measured inlet gauge pressure just before the Coriolis test meter and $P_{atm}$ is the atmospheric pressure at lab conditions. $\dot{V}_l$ and $\dot{V}_g$ are the volumetric flowrate of liquid and gas phase respectively.

Results obtained in aerated liquid tests are compared with the "bubble" model given by Hemp and Sultan[9]. A simplified schematic of an entrained air bubble in a liquid is shown in **Fig. 5.2**. Here a small sphere of material (density $\rho_s$) is situated in a pool of another material (density $\rho_l$). When the liquid with density $\rho_l$ is accelerated at A m/s$^2$, the sphere with density $\rho_s$ does not accelerate at same rate A m/s$^2$ but at rate A$_1$ m/s$^2$, where both are related as (page 36 of [29]),

$$A_1 = \frac{3\rho_l}{\rho_l + 2\rho_s} A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

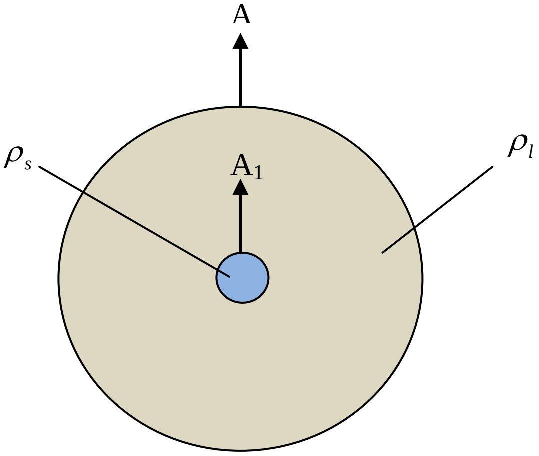


**Fig. 5.2 – Motion of small sphere in a liquid filled container**.

As clear from the equation 9, if the density of the sphere $\rho_s$ exceeds that of the surrounding fluid ($\rho_l$), the sphere “lags” behind the surrounding fluid; on other hand if $\rho_s < \rho_l$, the sphere “leads” ahead. In case of aerated liquids, $\rho_s << \rho_l$ and equation 9 gives,

$$A_1 = 3A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

Considering a unit volume of aerated mixture, with GVF equals $\alpha$, passing through the Coriolis meter, equation 10 suggests that gas bubble will vibrate with acceleration equaling three time the acceleration experienced by the rest of the surrounding fluid; this also suggests that in context of motion of sphere/bubble in a cross section of the vibrating tube, increased motion of the sphere/bubble compared to rest of the fluid will result in reduced level of participation in oscillation by rest of the fluid. This gives rise to reduced, apparent system inertia.

Rayleigh-Plesset equation in case of bubble acting as a harmonic oscillator surrounded by liquid gives[30],

$$\ddot{x} + \frac{3\gamma P_\infty}{R^2 \rho_l} x = 0 \quad \text{……………………………………………………………………} \quad (16)$$

Where x is the small displacement along the equilibrium axis of the bubble, $P_\infty$ is the far field liquid pressure, $R$ is the radius of the bubble, and $\gamma$ is the ideal gas specific heat ratio.

When compared to linear oscillator of the form,

$$\ddot{x} + \frac{k}{m} x = \ddot{x} + \omega^2 x = 0 \quad \text{………………………………………………………..........} \quad (17)$$

Where k is the spring constant, m is the effective mass oscillating, and $\omega$ is the resonant angular frequency.

It gives,

$$\omega = \frac{1}{R}\sqrt{\frac{3\gamma P_\infty}{\rho_l}} \quad \text{…………………………………………………………………......} \quad (18)$$

Along with,

$$m = m_e = 4\pi\rho R^3 \quad (19)$$

Equation (14) shows that when a bubble oscillates in the pool of the liquid, the effective mass oscillating is equal to three times the mass of liquid displaced by the bubble. This in turn results to no participation in oscillations by equal amount of liquid.

Therefore the meter measures apparent density and apparent mass flow rate given by,

$$\rho_a = \rho_l(1-3\alpha) \quad (20)$$

$$\dot{M}_a = \rho_l v A_t(1-3\alpha) \quad (21)$$

Where, $v$ is the velocity of the mixture through the meter, and $A_t$ is the cross sectional area of measuring tube.

Now if the density of liquid, $\rho_l$ is known and the apparent density value is given by the meter, the density error is given by,

$$E_d = \frac{\rho_a - \rho_l}{\rho_l} = -3\alpha \quad (22)$$

Since the true mass flow rate is,

$$\dot{M} = \rho_l(1-\alpha)vA_t \quad (23)$$

The mass flow error (neglecting the mass of gas) is given by,

$$E_m = \frac{\dot{M}_a - \dot{M}}{\dot{M}} = \frac{-2\alpha}{1-\alpha} \quad (24)$$

In the prior reasoning, the mass of the gas phase is considered negligible and hence is not accounted for in the model; also multi bubble dynamics is not included in the formulation. Another notable simplification is absence of any bubble-boundary interactions.

Experiments are conducted at three different liquid flowrates. All the experiments are started by introducing small quantities of air in single phase water flow and gradually increasing air quantities to reach required GVF. Experiments are stopped at the GVF which either corresponds to 10% error in mass flowrate reading or when pressure experienced prior to flow conditioner becomes higher than 15 psi; while the latter limit is dictated by the pressure handling capacity of transparent PVC pipes used in the setup, the former is frequently reported as the maximum error for any satisfactory multiphase metering.

Similar trends are seen from the separate tests conducted at liquid mass flow rates of 105 lb/m (439 bbl/day) (**Fig. 5.3**), 130 lb/m (541 bbl/day) (**Fig. 5.4**), and 150 lb/m (627 bbl/day) (**Fig. 5.5**). Negative mass flow errors are recorded for all the tests. Observed mass flow rates for all the cases lie between the actual (reference) and those predicted by the “bubble-model” (model MFR); this tends to suggest that the model does predicts the lower limit of mass flow errors. The discrepancies between the observed and predicted readings can be accounted to lack of multi-bubble dynamics and lack of bubble-structure interactions in the model.

In case of inlet swirl conditioner, observed errors are largest when compared to reference mass flow rate, and seems to follow the model rather well (Fig. 5.4 & Fig. 5.5). This can be due to coalesce of bubbles into a single air core; this reduces the deviation of the observed errors to that predicted by the model (which doesn't accounts for multi-bubble dynamics).

Flow conditioners affect the reading of the meter. This inference is unlike that observed in single phase flows; this suggests that the flow conditioners change the flow conditions rather than having any direct impact on the meter itself. In tests at each flow rate, inline mixer tends to homogenize flow and hence gives most accurate result compared to reference flow rate; on the other hand, inlet swirl tends to segregate flow and gives least accurate reading. Difference between readings with inline mixer and with no flow conditioner tends to decrease at higher flowrates. This may be explained due to increased shear rate, which tends to homogenize fluid distribution.

Use of inline mixer also increases the GVF limit for a particular error. For example, at liquid mass flow rate 105 lb/m (439 bbl/day), 10% error is achieved at GVF between 4 and 5, in case of inlet swirl; inline mixer gives 10% error after GVF 7. This can be a way of increasing the operational two-phase envelope of Coriolis meter. At liquid mass flow rate 150 lb/m (627 bbl/day), same analysis yields GVF between 5 and 6 (inlet swirl), and GVF 7 (inline mixer); this tends to suggest that effectiveness of inline mixer decreases at higher flow rates.

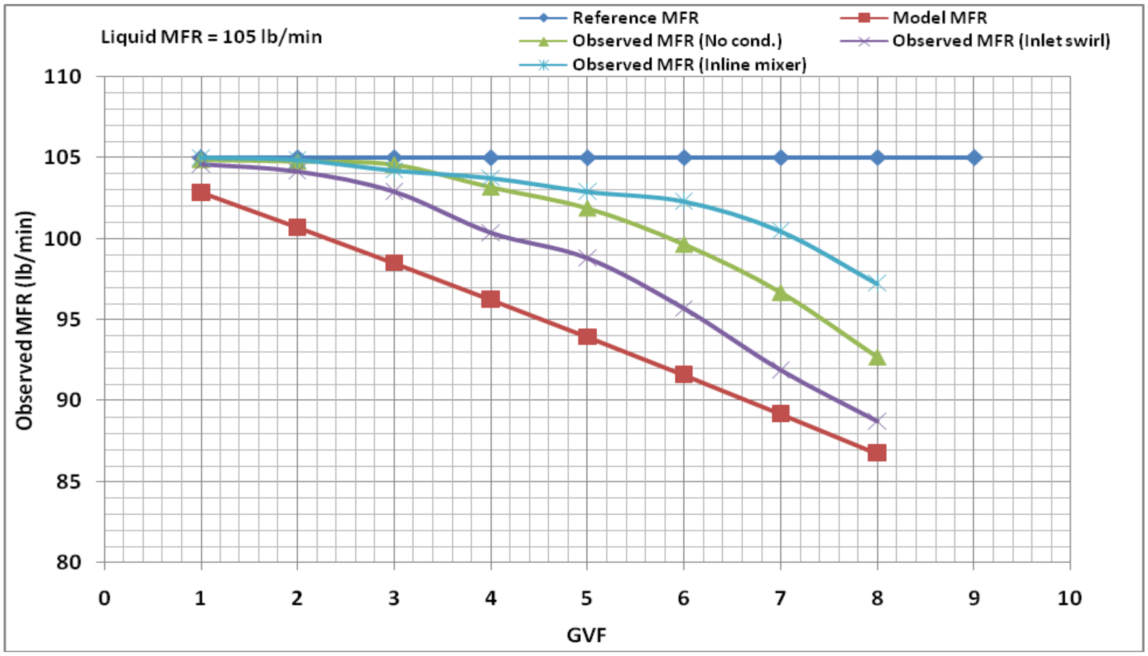


Fig. 5.3 – Aerated liquid test at flow rate, $Q_l$ = 105 lb/min.

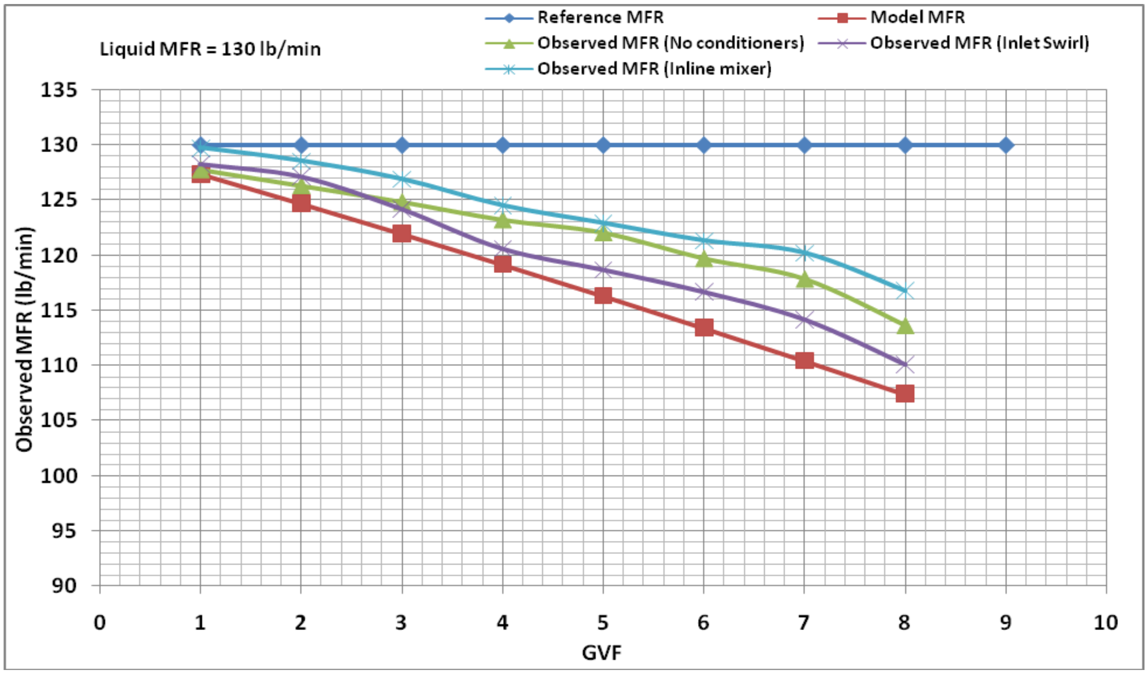


Fig. 5.4 – Aerated liquid test at flow rate $Q_l$ = 130 lb/min.

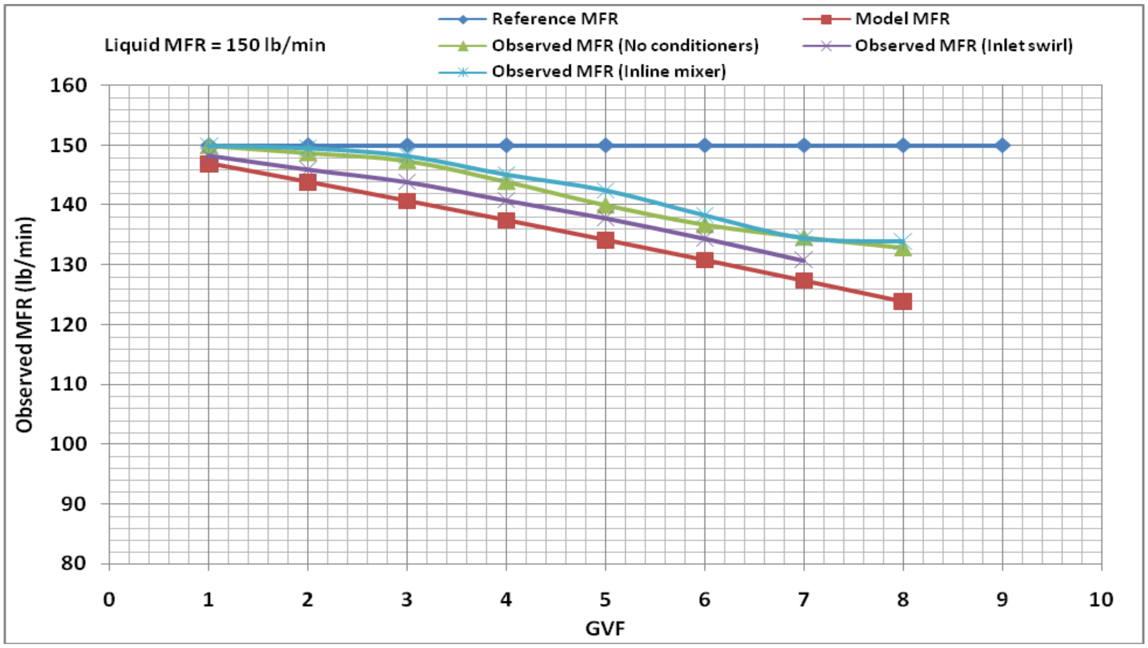


**Fig. 5.5 – Aerated liquid test at flow rate $Q_l$ = 150 lb/min.**

## 5.2 Wet gas tests

Wet gas is the generic name given to multi-phase fluids, where small quantities of liquids are present in flow stream comprised mainly from gas phase fluids. In field conditions, liquids may originate from the reservoir or may form from the gas phase itself in the form of condensates. In lab conditions, wet gas is generated by adding small quantities of liquid in an air flow. Similarly to aerated liquid tests, gas volume fractions (GVF) are calculated and recorded. Unlike in aerated liquids, there is no model available for Coriolis meter performance in wet gas. Though superficially, the only parameter that distinguishes wet gas from aerated liquids is GVF, the flow profile changes completely. In most cases the phase mixture is in annular flow regime; as such the models used in aerated liquids cannot be used for wet gas.

Tests are done at three different rates, 1 lb/m (19.2 Mscf/day), 1.5 lb/m (28.8 Mscf/day) and 2 lb/m (38.4 Mscf/day). The results of the investigation are presented in **Figs. 5.6 – 5.8**. A close observation of the plot shows that flow conditioners have no significant effect on the mass flow rate output of the meter; the reason seems to be the quick reversal of the flow back to annular even in presence of flow conditioners. As expected, error associated with the reading also increases as the GVF increases. Unlike aerated liquid tests, error in mass flow rate output is significant even at very low liquid contaminations (GVF~97). This may be due to high mass contrast between single phase gas and wet gas with even slight liquid contamination. At higher air flow rate (**Fig. 5.8**), inline mixer seems to cause an improvement in mass flow rate reading due to high shear rate involved with the flow.

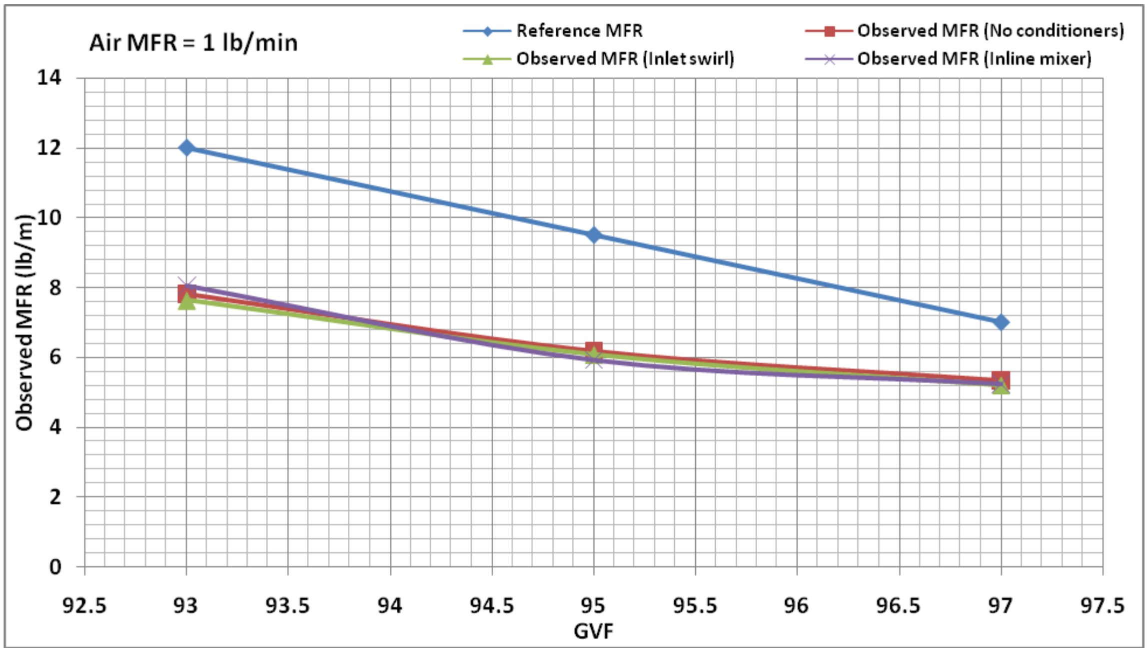


**Fig. 5.6 – Wet gas test at flow rate** $Q_g$ **= 1 lb/min**.

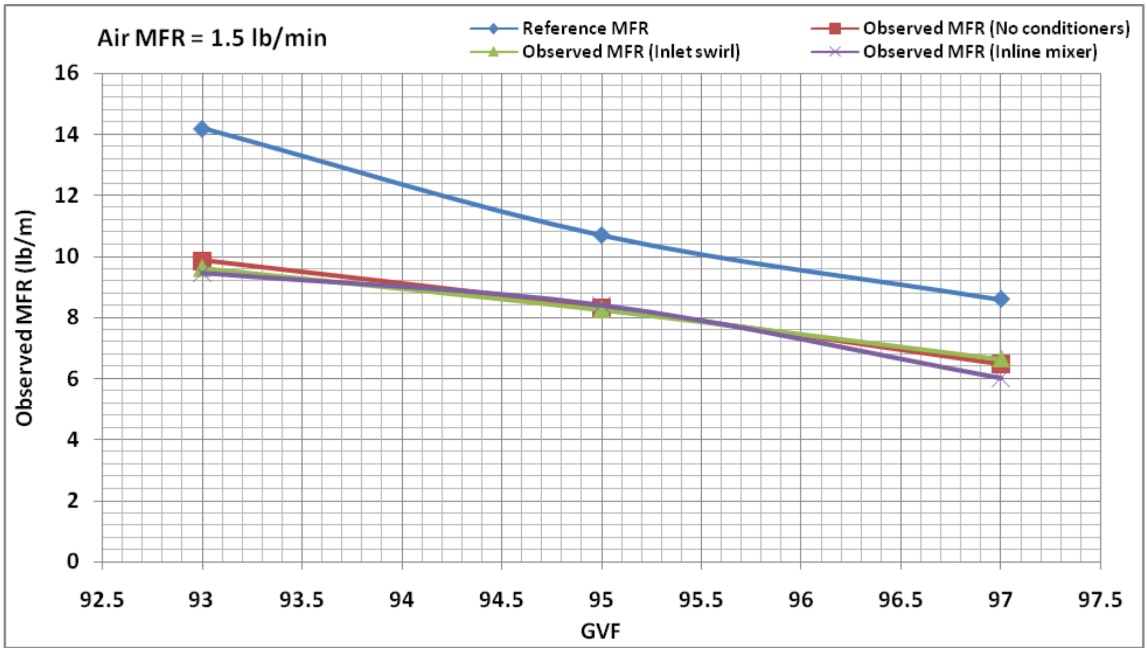


**Fig. 5.7 – Wet gas test at flow rate $Q_g$ = 1.5 lb/min.**

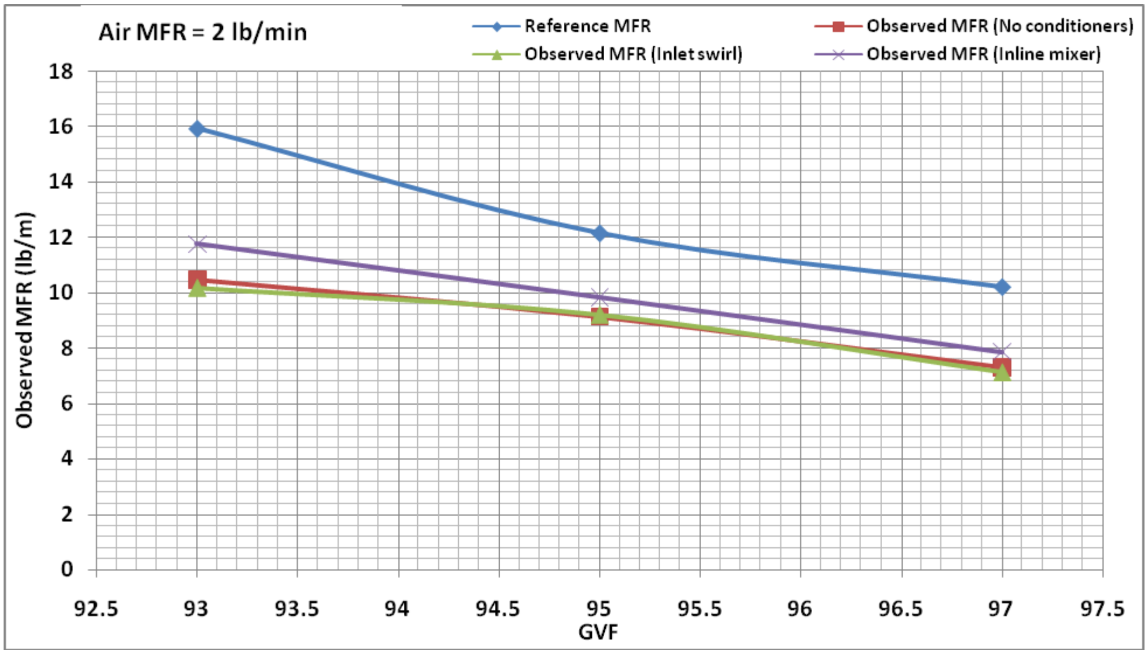


**Fig. 5.8 – Wet gas test at flow rate $Q_g$ = 2 lb/min.**

# CHAPTER VI

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Conclusions

From the results of this experimental investigation the following conclusions were reached:

1. Coriolis meter’s performance in single phase flows is excellent. Flow conditioners have no significant effect on accuracy.
2. Coriolis meter reports negative errors in case of aerated liquid flows for the gas volume fractions included in the work. The reason seems to be the relative motion between two phases.
3. Flow conditioners affect the accuracy of Coriolis meter in aerated liquid conditions. In most of the cases, inlet swirl decreases the accuracy while inline mixer has an opposite impact. Coriolis meter reports an error of 10% at GVF 7 to 8, when mass flow rate increase from 105 lb/m to 150 lb/m.
4. In aerated fluid tests, effect of flow conditioners on accuracy reduces with increased flow rate.
5. Coriolis meter reports negative errors in case of wet gas flows. Flow conditioners seem to have negligible effect on measurement accuracy on lower rates, with inline mixer showing improvement in highest flow rate used in testing.

Effect of flow conditioners on two-phase envelope has been experimentally determined. Flow conditioners are shown to have an impact on meter accuracy in aerated liquid flows, however small that might be; on the other hand, results from experiments with flow conditioners in wet gas don’t look promising. Coriolis meter is also shown to be able to handle two-phase flows without stalling.

## 6.2 Recommendations

Following recommendations are made based on results from this research:

1. Accuracy of Coriolis meters operating in two-phase flows should be investigated further with fluids having different viscosities and densities than water and air.
2. Current analytical prediction of Coriolis meter performance in two-phase flows lacks accuracy. Efforts should be made towards improvement.
3. Two-phase testing of Coriolis meters should be done at higher pressures and higher flow rates, simulating field conditions more realistically.
4. Further investigation of Coriolis meter performance should be done with vertical installation, to eliminate effect of buoyancy on readings.

# NOMENCLATURE

$\alpha$ = gas volume fraction

$\rho_a$ = apparent density

$\rho_l$ = liquid density

$\rho_s$ = sphere/bubble density

$\omega$ = resonant angular frequency

$\gamma$ = ideal gas specific heat ratio

$A_t$ = cross sectional area of measuring tube

$E_d$ = density error

$E_m$ = mass flow rate error

$GVF$ = gas volume fraction

$k$ = spring constant

$MFR$ = mass flow rate

$\dot{M}$ = actual mass flow rate (gas mass neglected)

$\dot{M}_a$ = apparent mass flow rate

$\dot{M}_g$ = gas mass flow rate

$\dot{M}_l$ = liquid mass flow rate

$P_{atm}$ = atmospheric pressure

$P_{inlet}$ = pressure at the inlet of Coriolis meter

$P_{\infty}$ = far-field pressure

$Q_g$ = gas mass flow rate

$Q_l$ = liquid mass flow rate

$R$ = radius of sphere/bubble.

$T_g$ = gas temperature

$\dot{V}_g$ = gas volumetric flow rate

$\dot{V}_l$ = liquid volumetric flow rate

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