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Wet Gas Flow Measurements with Mixtures of Natural Gas, Hydrocarbon Liquids and Water

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ABSTRACT

This paper presents an overview of preliminary data and results gathered from a new multiphase test facility at Colorado Engineering Experiment Station, Inc. (CEESI). The goal of the project is to determine the feasibility of obtaining accurate multiphase test results when the fluids are natural gas, hydrocarbon liquids and water. A small 50 mm (2 inch) pilot test facility has been constructed to understand the operational characteristics and the problems associated with handling multiphase fluids. The data presented herein is for a classical (Herschel) venturi meter operating under multiphase conditions.

The preliminary results obtained on this pilot test facility are sufficiently encouraging that designs for increased fluid handling capacity and increased piping sizes are being made.

INTRODUCTION

CEESI began its flow measurement work as a spin-off from the University of Colorado in 1965. At that time, the work entailed performing flow meter calibrations with compressible fluids, namely air. From the early days until present, the testing capabilities have expanded to include increased air flow rate calibration capacity, high pressure water calibration capacity at 140 bar (2000 psi), high volume natural gas flow rate calibration capacity at flow rates exceeding 28 million SCMD (1 billion SCFD).

In the late 1990's, CEESI began construction of a two-phase testing facility that utilized natural gas and liquid decane (C10) as the operating fluids. Most of the work performed in this wet-gas facility has been sponsored by an industry JIP, manufacturers and users of specific wet-gas flow meters, and performance evaluations of various compact gas-liquid separators. In 2002, CEESI expanded a portion of the wet-gas facility to include water and brine injection for the study of hydrate formation and the possible remediation of hydrate blockage problems.

In 2004, CEESI constructed the small 50 mm (2 inch) multiphase test facility described in this paper. The preliminary results obtained on this pilot test facility are sufficiently encouraging that designs for increased fluid handling capacity and increased piping sizes are being made.

FACILITY DESIGN

Figure 1 shows a simplified block diagram of the multiphase test facility. The piping size at the test meter locations is 50 mm (2 inch). The natural gas is continuously recirculated around the test loop by positive displacement compressors at static pressures of 6 to 83 bar (100 to 1200 psi). For the present, the natural gas flow rate is measured by an orifice meter. This orifice meter will soon be replaced with a turbine flow meter which will allow for easier test loop operation. The test temperatures are, at present, ambient to 30ºC (50ºF) above ambient.

The liquids used to date are water and Stoddard solvent. Stoddard solvent is a mixture of liquid hydrocarbons which consists mainly of C9 through C13. The detailed analysis of the Stoddard solvent shows more than 100 components, but many of these are in very minute amounts.

Not shown in Figure 1 is the equipment and piping necessary to “stabilize” or equilibrate the liquids with the natural gas. Prior to beginning a test, natural gas is allowed to pass through the liquids while those liquids are in their storage vessels. This is done at the pressure that the test will be conducted. The Stoddard solvent will absorb several of the components from the natural gas stream which results in a less dense liquid. Water will also absorb some natural gas components, but at much smaller quantities.

The liquid is injected into the multiphase loop by over pressurizing the storage vessel with either natural gas or nitrogen. The mass flow rate and density of each fluid stream is individually measured with 12 mm (0.5 inch) coriolis meters. The combined liquid mass flow rate and density is again measured with a larger 50 mm (2 inch) coriolis meter. In these initial tests, the “mixture” coriolis meter performed well on sensing the total liquid mass flow rate, but did not perform as well on the mixture density. At small liquid flow rates, the water would accumulate in the low portion of the vibrating tubes of the coriolis meters creating a false (high) indication of the liquid density. Multiple sized coriolis meters are planned to be used in the future to eliminate this density sensing problem.

The combined liquid is injected into the test loop upstream of the test meters. The natural gas carries (or drags) the liquids through the test loop to a 3-phase separator. The gas returns to the inlet of the circulation compressors and the liquid remains in the separator. For the test results reported in this paper, the 3-phase separator is acting only as a liquid catch tank. The testing is accomplished in a batch operation where the liquids are passed only once through the test meters. After a specific test, all liquid is transferred to an ambient storage vessel where good separation of the water and hydrocarbon liquid can occur. The hydrocarbon liquid is reclaimed and the water is discarded. In the future, as the operational characteristics of the 3-phase separator are well understood, the liquids will be returned to their storage vessels so that continuous testing can occur.

For the data reported herein, the classical (Herschel) venturi was installed in the first test meter location as shown in Figure 1. Two other proprietary head type flow meters were installed in test meter locations 2 and 3.

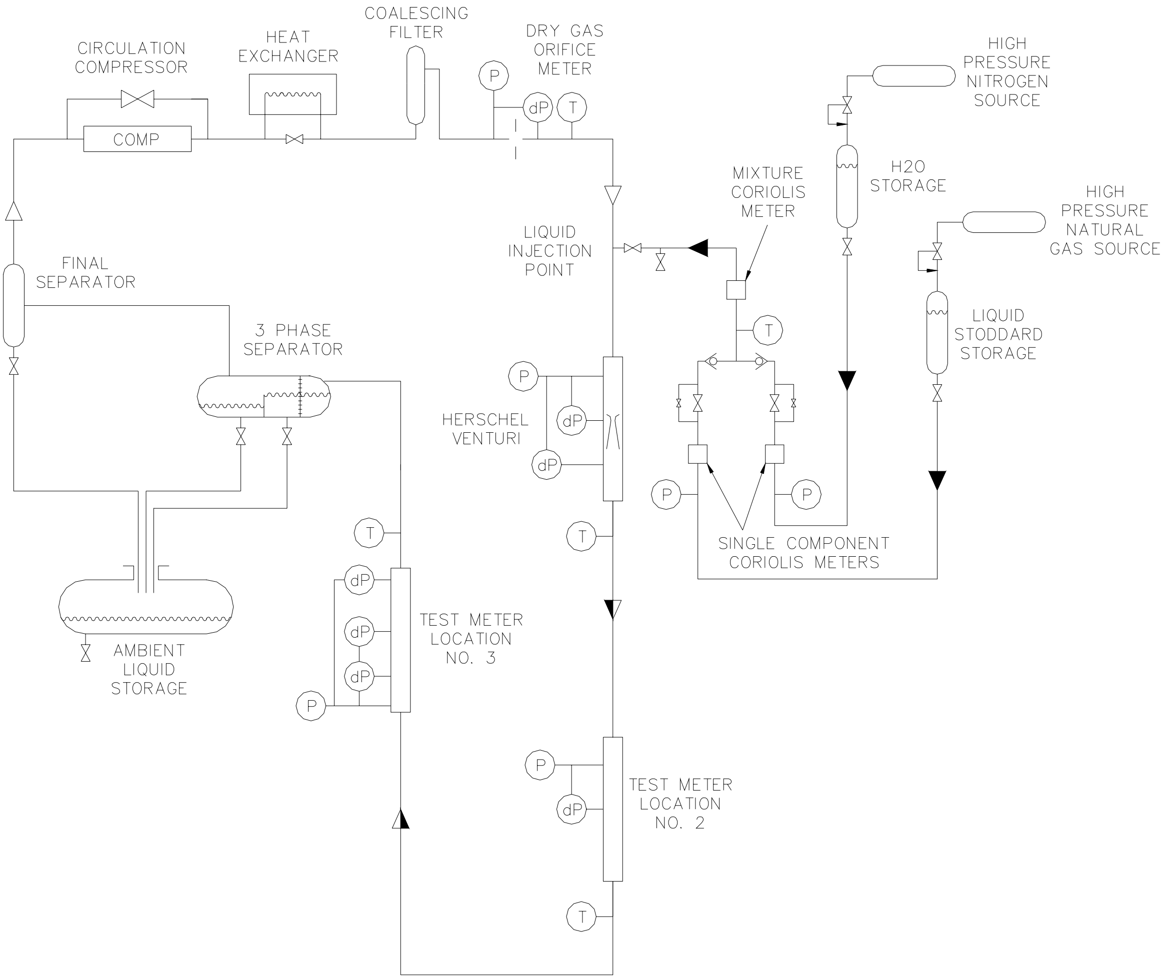

FIGURE 1
BLOCK DIAGRAM OF MULTIPHASE TEST FACILITY

FLUID PROPERTIES

As stated above, the fluids used in these multiphase tests are natural gas, a hydrocarbon liquid (Stoddard solvent), and water. The composition of the natural gas varies only slightly from test to test and the average composition is shown in Table 1. Also shown in Table 1 is a gross classification of the liquid components where all carbon numbers are grouped together. In reality there are over 100 components in the hydrocarbon liquid (Stoddard solvent), but many of them are miniscule.

The water used during this experimental data can be classified as pure. It is the facility drinking water, and contains only a very small amount of dissolved salts.

The density of the natural gas at any specific location in test facility is calculated by the methods described in reference [3]. The density calculation requires the measured pressure and temperature of the gas at that specific location and the gas composition.

TABLE 1
Fluid Components

Natural Gas Component	Mole Percent	Liquid Component	Percent Mass
Methane	84.8811	C3	0.0895
Ethane	10.9971	C4	0.0643
Propane	1.3741	C5	0.171
i-Butane	0.0417	C6	0.193
n-Butane	0.0551	C7	0.337
i-Pentane	0.0029	C8	0.862
n-Pentane	0.0020	C9	2.510
C6's	0.0005	C10	27.77
C7's	0.0002	C11	55.72
C8's	0.0001	C12	10.30
C9+	0.0336	C13	1.981
Carbon Dioxide	2.1653		
Nitrogen	0.4463		

Figure 2 shows the specific gravity of the water and Stoddard solvent. The lines shown on this figure are a best linear fit to the density as output from the single component coriolis meters for all test data. The sloping lines agree well with the expected thermal expansion of the fluids, and the absorption of natural gas components by the Stoddard solvent.

For those test conditions where mixed liquids were flowing through the venturi, and the liquid flow rate was too small for the mixture coriolis meter to measure the mixture accurately, the mixture density was calculated from single component coriolis meters on a volumetric base.

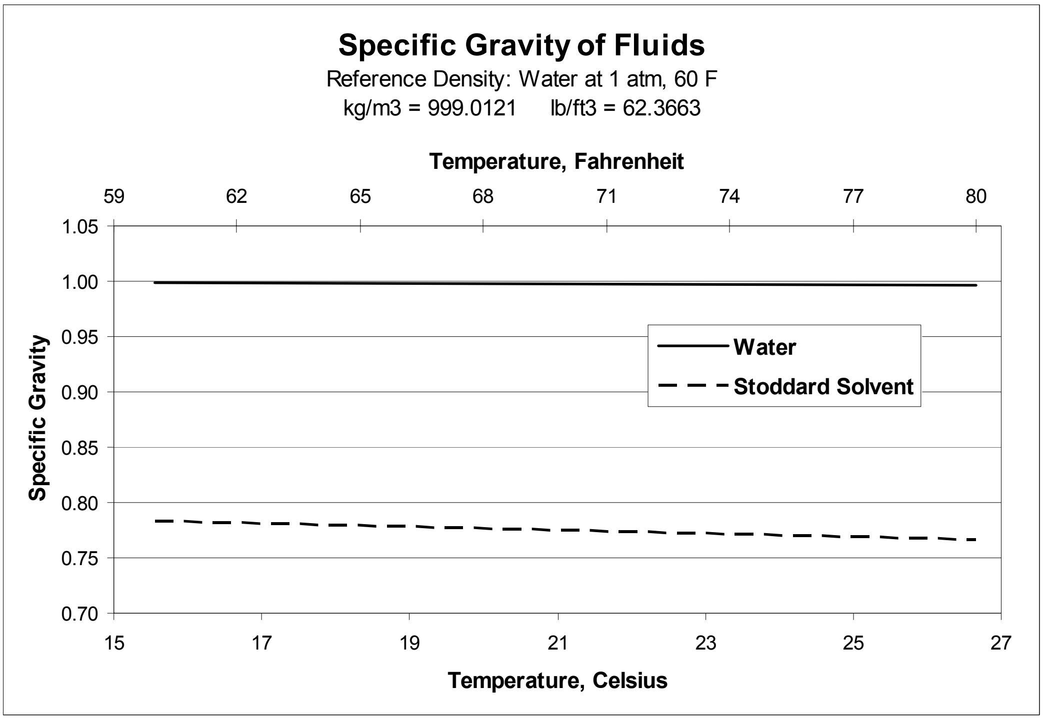

FIGURE 2
SPECIFIC GRAVITY OF TEST LIQUIDS

TEST RESULTS

The test data reported herein was obtained on the classical (Herschel) venturi shown in Figure 3. The material of construction is stainless steel.

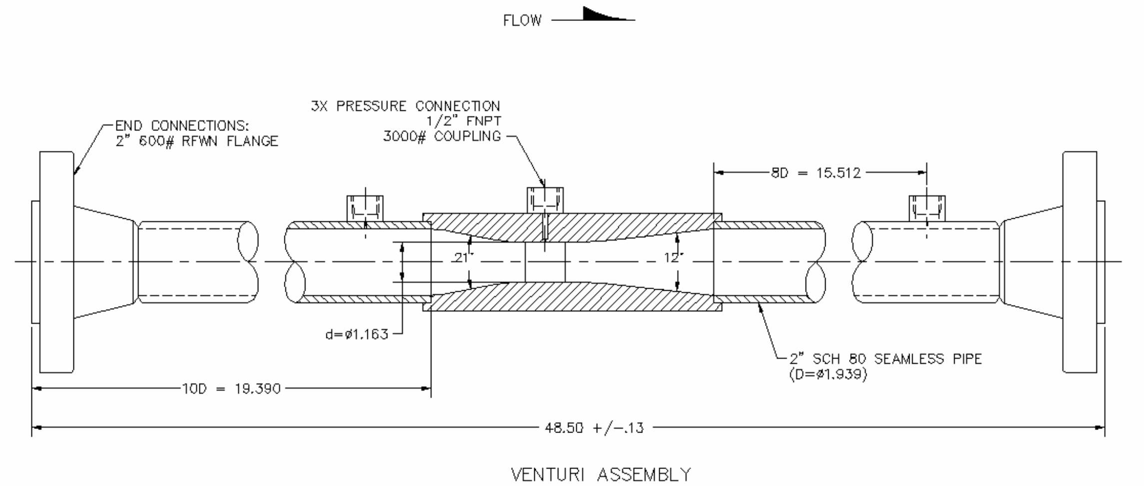

FIGURE 3
50 mm (2 inch) Classical (Herschel) Venturi
Pipe Dia: 49.22 mm (1.938 inch)
Throat Dia: 29.54 mm (1.163 inch)
Beta Ratio: 0.60

Table 2 gives a short summary of the flowing conditions that existed during this test program. The values shown for GVF and % Water were target numbers that were desired. In reality, the true value of these numbers varied slightly as the conditions in the test facility stabilized.

TABLE 2
Test Matrix

Static Pressure Range	12.3 to 14.1 bar (178 to 205 psia)
Temperature Range	18ºC to 26ºC (64ºF to 79ºF)
GVF --- Gas Volume Fraction	0.980, 0.985, 0.990, 0.995, 1.000
% Water	0%, 25%, 50%, 75%, 100%

The following equations and definitions are listed for the reader's convenience. A list of symbols and units are given at the end of this paper.

% Water is also known as the Water in Liquid Ratio (WLR) and is defined as the ratio of water volumetric flow rate to total liquid volumetric flow rate at operating conditions.

Superficial Gas Velocity (Vsg) is the gas velocity that would exist in the pipe if there were no liquid present.

Superficial Liquid Velocity (Vsl) is the liquid velocity that would exist in the pipe if there were no gas present.

W_O is the gas mass flow rate as measured by the orifice meter where no liquids are present.

W_V is the gas mass flow rate as calculated by pressure, temperature, and differential pressure at the venturi meter. The differential pressure at the venturi will be increased due to the presence of any liquid.

Gas Mass Flow Ratio (GMFR) is the ratio of the venturi gas mass flow rate (W_V) to the orifice gas mass flow rate (W_O). The venturi gas mass flow rate will be artificially high due to the presence of liquids.

$$\mathrm{GMFR} = \frac{W_V}{W_O}$$

Gas Volume Fraction (GVF) is the ratio of the actual volumetric flow rate of gas to the actual volumetric flow rate of both the gas and liquid.

$$\mathrm{GVF} = \frac{Q_G}{Q_G + Q_L}$$

Densomeric Gas Froude number (Fr_G) a dimensionless parameter and can be thought of as the ratio of inertial force of the moving gas to the gravity force.

$$Fr_G = \frac{Vsg}{\sqrt{gD}}\sqrt{\frac{\rho_G}{(\rho_L - \rho_G)}}$$

Densomeric Liquid Froude number (Fr_L) a dimensionless parameter and can be thought of as the ratio of inertial force of the moving liquid to the gravity force.

$$Fr_L = \frac{Vsl}{\sqrt{gD}}\sqrt{\frac{\rho_L}{(\rho_L - \rho_G)}}$$

Lockhart Martinelli number (X) is a dimensionless parameter that has been proven to be a successful correlating parameter in wet-gas and multiphase flow. There are several equivalent methods to calculate X as shown below.

$$X = \frac{Q_L}{Q_G}\sqrt{\frac{\rho_L}{\rho_G}} = \frac{Vsl}{Vsg}\sqrt{\frac{\rho_L}{\rho_G}} = \frac{W_L}{W_G}\sqrt{\frac{\rho_G}{\rho_L}} = \frac{Fr_L}{Fr_G}$$

Figure 4 is a flow regime map that depicts the type of two-phase flow that is expected to exist in a horizontal piping system. The solid lines show the approximate regions of stratified, annular, and slug flow. Also shown on this figure (solid symbols) is the data obtained during this test program.

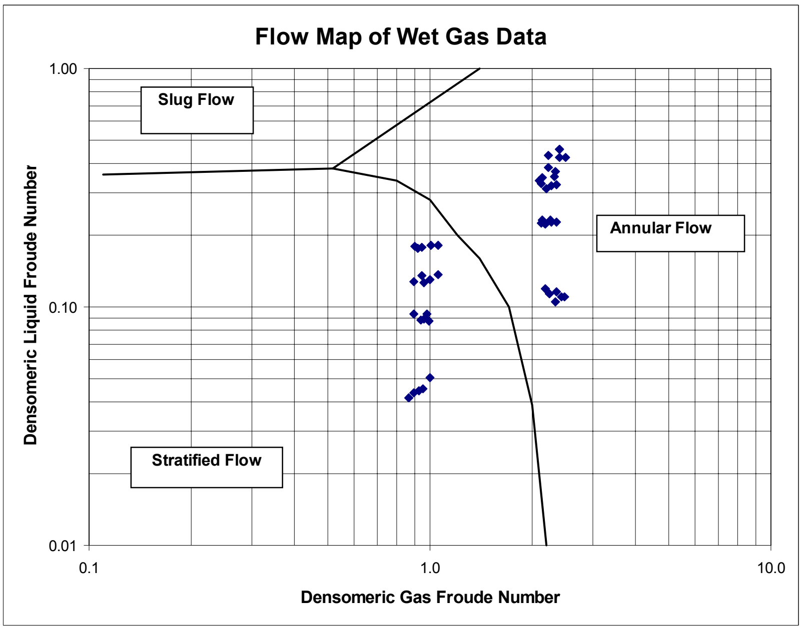

FIGURE 4
FLOW PATTERN MAP OF TEST DATA

Figure 5 shows the GMFR versus Lockhart Martinelli number for the test data. The shape and shading of the symbols indicate the amount and type of liquid present in the pipe. The % Water ranges from 0 to 100. When the % Water is zero, it means that all of the flowing liquid is Stoddard solvent. When the % Water is 100, it means that all the flowing liquid is water. Also shown on this figure is data from references [1] and [2]. The data from these two references are for a 100 mm (4 inch) classical venturi with a 0.40 Beta ratio.

As can be seen, there is a systematic difference between the present data and reference [1]. The difference is probably due to the different fluids involved and not so much the pipe size and Beta ratio of the venturis. The present data is natural gas, Stoddard solvent, and water. The fluids involved with reference [1] are nitrogen for the gas phase and diesel oil as the liquid phase. Fluid properties such as surface tension and viscosity will cause differences in the GMFR.

The fluids used in reference [2] were natural gas and liquid decane, but 0.07 was the maximum Lockhart Martinelli number obtained. By projecting the line from reference [2], it appears that there is some general agreement between reference [2] and the present data.

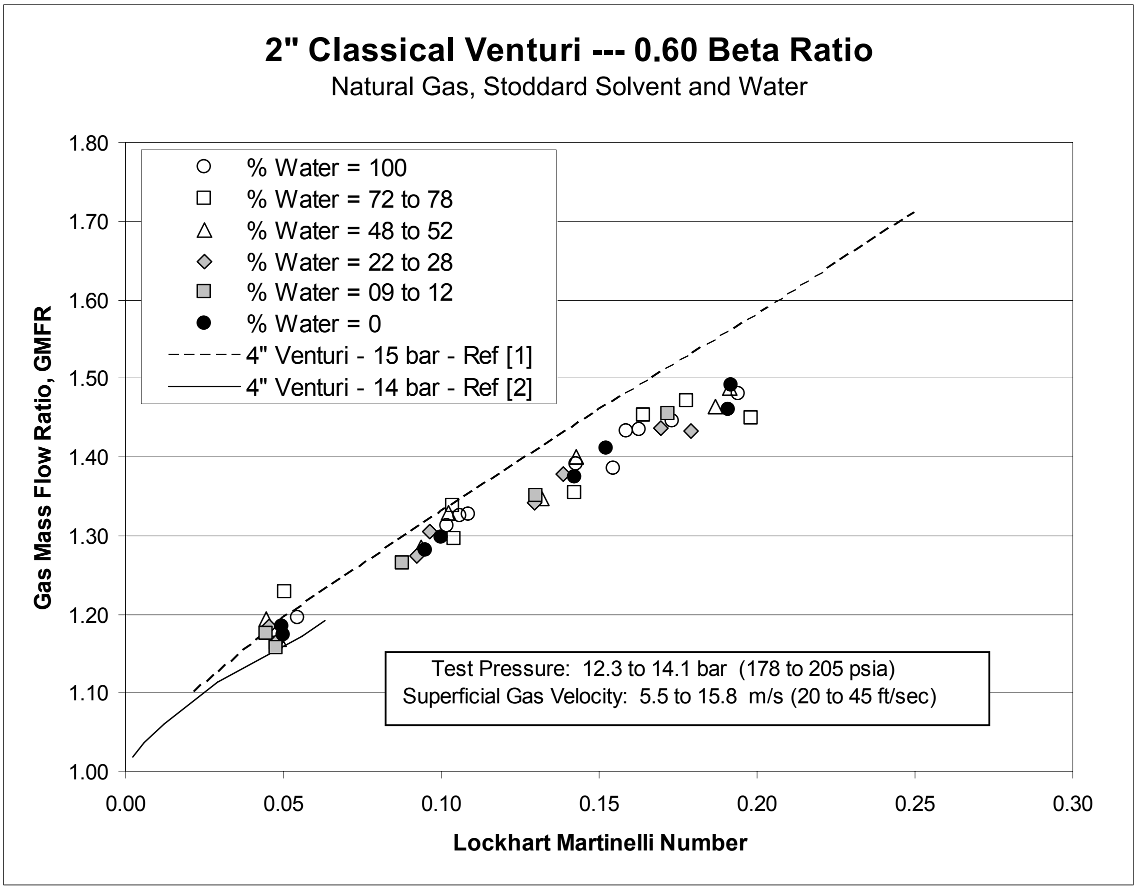

FIGURE 5

Figure 6 shows the change in the venturi differential pressure at the two superficial gas velocities where test data was obtained. As expected the differential pressure increases from the dry flowing condition as the amount of liquid increases (or GVF decreases). In this figure, the differential pressures were normalized to the average velocity that existed during the test.

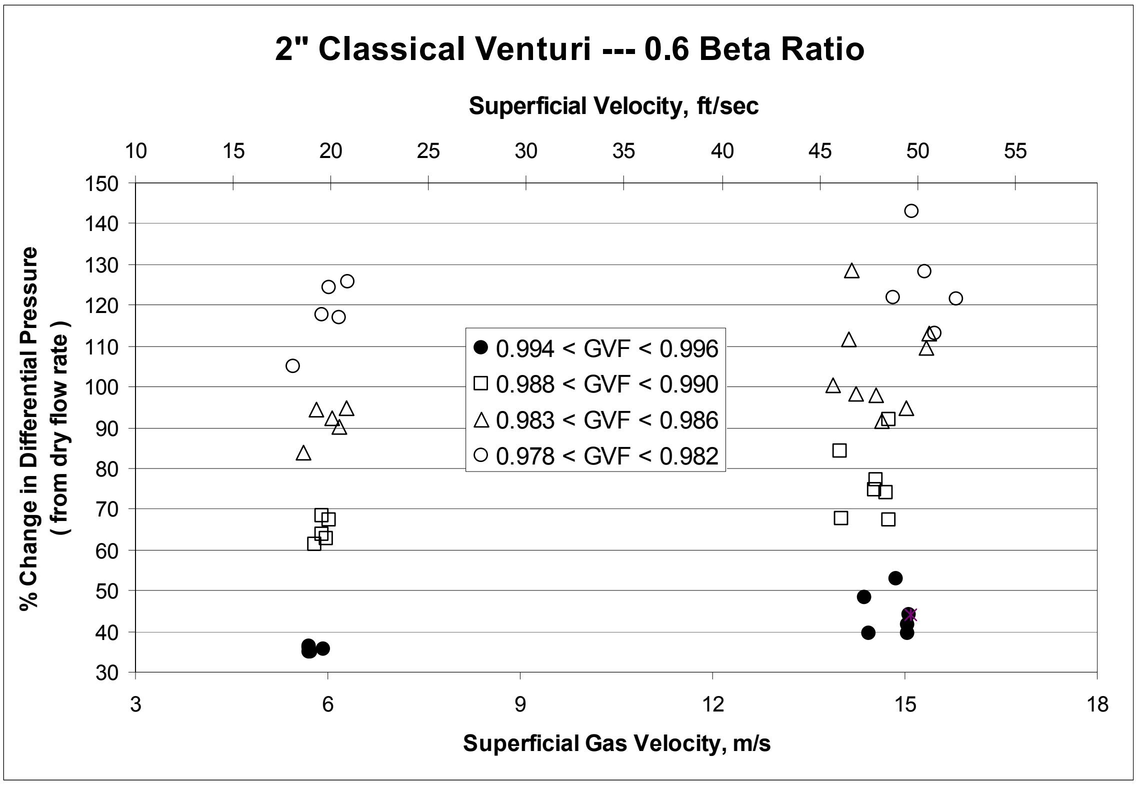

FIGURE 6

Figure 7 shows a portion of the data at the high gas superficial velocity. Shown are three different % Water conditions at three different values of GVF. As can be seen, the amount of water causes a significant increase in the differential pressure. However, a close examination of the data shows that a consistent percent increase in differential pressure is not present for each GVF level. Most likely, the test facility is creating a portion of this non-consistency with its level of stability and its data acquisition methods. However, other factors such as the flow regime can and will affect the differential pressure.

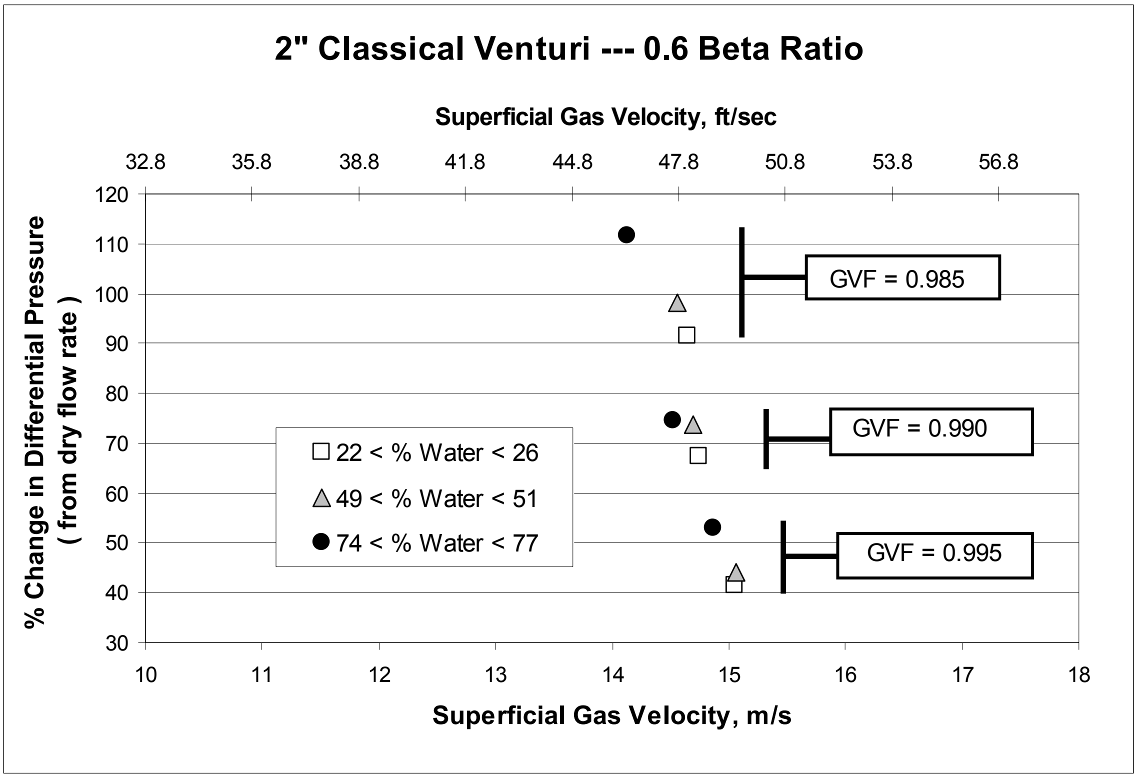

FIGURE 7

CONCLUSION

The initial testing conducted on this small pilot multiphase test facility seems to produce data of sufficient quality that further multiphase flow experiments can performed. CEESI is beginning to design facility modifications that will increase the multiphase testing capacity and allow for better control of testing conditions.

SYMBOLS AND UNITS

Symbol	Name	SI Units	English Units
Fr_G	Gas Froude number	dimensionless	dimensionless
Fr_L	Liquid Froude number	dimensionless	dimensionless
D	Pipe diameter	m	ft
GMFR	Gas mass flow ratio	dimensionless	dimensionless
GVF	Gas Volume Fraction	dimensionless	dimensionless
g	Gravitational constant	$1\ (kg \cdot m)/(N \cdot s^2)$	$32.1405\ (lbm \cdot ft)/(lbf \cdot sec^2)$
Q_G	Actual gas volume flow rate	m^3/s	ft^3/sec
Q_L	Actual liquid volume flow rate	m^3/s	ft^3/sec
Vsg	Superficial gas velocity	m/s	ft/sec
Vsl	Superficial liquid velocity	m/s	ft/sec
W_G	Gas mass flow rate	kg/s	lbm/sec
W_L	Liquid mass flow rate	kg/s	lbm/sec
W_O	Orifice gas mass flow rate	kg/s	lbm/sec
W_V	Venturi gas mass flow rate	kg/s	lbm/sec
X	Lockhart Martinelli number	dimensionless	dimensionless
β	Beta ratio, d/D	dimensionless	dimensionless
ρ_G	Density of gas	kg/m^3	lbm/ft^3
ρ_L	Density of gas	kg/m^3	lbm/ft^3

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