EFFECT OF LIQUID ENTRAINMENT ON THE ACCURACY OF ORIFICE METERS FOR GAS FLOW MEASUREMENT

EFFET DE L'ENTRAÎNEMENT DE LIQUIDE SUR LA PRÉCISION DES DÉBITMÈTRES À DIAPHRAGME EN MESURES DES DEBITS DE GAZ

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ABSTRACT

This paper presents the results of a study to show that a small amount of liquid entrainment in an orifice meter can affect the accuracy of gas flow measurement. A series of tests, sponsored by Chevron Petroleum Technology Company, was conducted under controlled conditions at the Colorado Engineering Experiment Station, Inc. (CEESI) air flow calibration facility to study this effect. Eight-inch orifice meters were selected for the experiments. The tests were conducted at 4.13 MPa (600 psia) over the orifice Reynolds number range from 4 to 9 million using two horizontally mounted orifice meters. Water was injected at a controlled rate upstream of the orifice meter to simulate field conditions. It was found that the presence of a small amount of liquid in the gas stream caused the orifice meters to read a lower gas flow measurement by as much as 1.7% depending on the beta ratio and the liquid rate.

RESUME

Cette contribution présente les résultats d'une étude visant à démontrer qu'une petite quantité d'entraînement liquide dans un débitmètre à diaphragme peut influer sur la précision des mesures des débits de gaz. Une série de tests commanditée par la Chevron Petroleum Technology Company, a été réalisée sous conditions contrôlées au centre de calibration d'écoulement d'air à la Colorado Engineering Experiment Station, Inc. (CEESI) afin d'étudier ce phénomène. Pour les tests on a choisi des débitmètres à diaphragme de huit pouces. Les tests ont été réalisés à une pression de 4.13 MPa (600 psia) dans la gamme de nombres de Reynolds de 4 à 9 millions avec l'utilisation de deux débitmètres montés de façon horizontale. L'injection d'eau à un taux contrôlé en amont du compteur servait à simuler les conditions de champ. On a trouvé que la présence d'une petite quantité de liquide dans le courant de gaz a amené les débitmètres à sous-évaluer les mesures, les erreurs pouvant atteindre jusqu'à 1.7%, selon le rapport beta et le taux liquide.

This paper extends the earlier low pressure laboratory work by Ting to a horizontally mounted 20.32 cm (8-inch) orifice meter at 4.13 MPa (600 psia) to simulate field operating conditions. A series of tests was conducted under controlled conditions at the Colorado Engineering Experiment Station, Inc. (CEESI) air flow calibration facility to study this effect for orifice Reynolds numbers from 4 to 9 million and beta ratios of 0.5 and 0.7.

EXPERIMENTAL SYSTEM AND PROCEDURES

The calibrations were performed using a blow down system to supply air to the test section. Systems of this type are typically used to calibrate flowmeters using either a primary calibration method or by using a secondary standard such as a critical flow venturi.[14-20] When secondary calibrations are done with a critical flow venturi, the calibration uncertainty is usually quoted as ±0.5%. In the case of the tests reported here, two orifices were first calibrated with a critical flow venturi using dry air. A turbine meter was also calibrated using dry air. In subsequent tests when water was injected into the line, the turbine meter was used to determine the volumetric flow rate of the dry air component. Temperature and pressure measurements in the vicinity of the turbine meter were used with a state equation for air to calculate density. This was then multiplied by the volumetric flow rate to determine the mass flow rate of the dry air component.

Wet air tests were performed by injecting water directly into the line upstream of the orifices (see Figure 1). The flow rate of water was determined with needle valves that had previously been calibrated in a high pressure water facility.[21] That calibration process consisted of measuring the flow rate through a valve when applying a 344.7 kPa (50 psi) differential pressure across the valve at several different valve stem positions as determined with a micrometer adjusting screw on the valve. The data was fit, and the fit was used to calculate the mass flow rate of water in the wet air tests.

Water was injected into the test section through a horizontal 9.525 mm (3/8") tube having seven sets of radial holes drilled into the tube (see Figure 2). Each set consisted of eight holes spaced at 45°. The spacing between hole sets along the length of the tube was one inch. Two hole sizes were used depending on the desired mass fraction or ratio of the mass flow rate of water to the mass flow rate of dry air. For mass fractions from 0.0012 to 0.021, a 1.27 mm (0.05") hole size was used, and for mass fractions from 0.0002 to 0.0011, a 0.508 mm (0.02") hole size was used. No attempt was made to spray the water into the flow field. Rather, any dispersion of the water was caused by the flow of air past the tube. Although the water injection was not visually observed, it was felt that water which did not evaporate probably accumulated along the bottom half of the pipe or on the orifice. The dew point of the air downstream of the water injection point was also not measured.

In a typical calibration, flow was established at steady conditions and when thermal equilibrium was achieved, the flow rates of both the dry air and water were measured. The discharge coefficient of the orifice was initially established with no water flow by

$$C_{dry} = \frac{4 q_{mdry} \varepsilon_2 d^2}{\pi} \sqrt{\frac{1-\beta^4}{2 \Delta p \rho_{f2}}} \qquad (1)$$

where, C_{dry} = the discharge coefficient when the flowing fluid is dry air

q_{mdry} = the mass flow rate of dry air as determined with a critical flow venturi

e_2 = the expansion factor based on the downstream pressure given by

$$\varepsilon_2 = \sqrt{1+\frac{\Delta p}{p_2}} - \left(0.41+0.35\beta^4\right)\frac{\Delta p}{\kappa p_2 \sqrt{1+\frac{\Delta p}{p_2}}}$$

π = 3.141592654

d = the throat diameter of the orifice
β = beta ratio, d/D
D = the interior diameter of the pipe
Δp = the differential pressure across the orifice = $p_1 - p_2$
ρ_{f2} = the density of the dry air based on the pressure, p_2, and temperature, T_2, downstream of the orifice
κ = the isentropic exponent for dry air

When water was injected into the line, the discharge coefficient was calculated using the following equation:

$$C_{wet} = \frac{4q_{mdry}\varepsilon_2 d^2}{\pi}\sqrt{\frac{1-\beta^4}{2\Delta p\rho_{f2}}} \tag{2}$$

A major difference in this case is that the flow rate of the dry air component (q_{mdry}) is determined with the turbine meter using the pressure and temperature measurements at the turbine. The density of wet air at the orifice was calculated using the equation of state for dry air. Because free water was present, the downstream pressure, differential pressure, fluid density and viscosity at the orifice differed from what would have been observed had the air been truly dry. Consequently, by using dry air state equations, an apparent shift was introduced in the discharge coefficient.

The discharge coefficient was determined in both the dry air and wet air cases as a function of the orifice throat Reynolds number, Rd, given by

$$Rd = \frac{\rho v d}{\mu} = \frac{4q_{mdry}}{\pi d\mu} \tag{3}$$

where μ = the dynamic viscosity of dry air based on p_2 and T_2.

When the mass flow rate was calculated from orifice measurements, the calculation process involved first calculating the dry air density, viscosity and k using p_2 and T_2. A first estimate of the flow rate was then made by setting $C_{dry} = 0.6$ and calculating q_{mwet} using the equation

$$q_{mwet} = \frac{\pi}{4}C_{dry}\varepsilon_2 d^2\sqrt{\frac{2\Delta p\rho_{f2}}{1-\beta^4}} \tag{4}$$

The throat Reynolds number was calculated using equation (3), and a second estimate of the discharge coefficient was obtained from the functional relationship between C_{dry} and Rd which was determined under reference conditions with dry air. A second estimate of the mass flow rate was then calculated with equation (4). This process of calculating the flow rate, calculating a throat Reynolds number, calculating a new estimate of the discharge coefficient and then calculating a new flow rate was repeated until the flow rate calculations converged (usually by the third iteration). It is consistent with current practice.[1-3]

The above procedures resulted in values for predicted discharge coefficients and flow rates that could be compared to the reference dry air discharge coefficients and true dry air mass flow rates. These comparisons were carried out for two orifices, one having $\beta = 0.5$ and the other having $\beta = 0.7$ at a variety of water to dry air mass fractions.

RESULTS AND DISCUSSION

The purpose of these tests was to observe the relative shifts of orifice discharge coefficients and flow rate caused by water injection when using dry air fluid properties. Air flow rate data for Reynolds numbers from 4 to 9 million were collected for 20.32 cm (8-inch) orifice meters with 0.5 and 0.7 beta ratios at a nominal 4.13 MPa and 15.6°C (600 psia and 60°F). A controlled amount of water was injected upstream of the orifice meter during the experiments. The water injection rate with respect to the air injection rate is expressed in terms of mass ratio:

$$\text{Mass Ratio} = \frac{(\text{Water mass flow rate})}{(\text{Air mass flow rate})} \tag{5}$$

For each sequence of tests, a fixed mass ratio was set over the entire air flow rate range. Seven mass ratios were selected for the tests. Table 1 summarizes the test parameters used in the experiments.

Table 1. 20.32 cm (8-inch) Orifice Meter Liquid Entrainment Experiment — Test Parameters

Gas	Liquid	Pressure MPa (psia)	Temperature °C (°F)	Beta Ratio	Gas Flow Range (Orifice Reynolds Numbers)	Mass Ratio
Air	Water	4.13 (600)	15.6 (60)	0.5 and 0.7	4,000,000–9,000,000	0.0002, 0.0005, 0.0008, 0.001, 0.005, 0.01, and 0.02

For each beta ratio, the orifice meter was calibrated with dry air at the beginning of the tests. Orifice meter discharge coefficients at dry air conditions (C_{dry}) were developed over the orifice Reynolds number range. For example, Figure 3 shows the C_{dry} calibration curve for a 0.5 beta ratio over a Reynolds number range from 4–9 millions. The C_{dry} data were fit with a second degree equation in terms of the Reynolds number (Rd) and in the case of $\beta = 0.5$, the following equation was obtained.

$$C_{dry} = 0.603483 + 7.7 \times 10^{-11}\,\text{Rd} + 1.28 \times 10^{-14}\,\text{Rd}^2 \tag{6}$$

The meters were then calibrated at wet conditions with a constant water injection rate. However, the fluid density of the wet stream was assumed dry without the water additions. This was done to simulate actual field computation methods where the amount of liquid entrainment in the orifice meters was generally ignored. A set of orifice meter discharge coefficients (C_{wet}) were thus obtained.

To characterize orifice meter performance, the orifice meter discharge coefficients obtained by the experiments at wet conditions (C_{wet}) were compared with the dry discharge coefficients (C_{dry}). The wet air discharge coefficient deviation from the dry air discharge coefficient for the orifice meter was calculated with Equation (7).

$$\%\text{C Deviation} = \frac{(C_{wet} - C_{dry})}{C_{dry}} \times 100 \tag{7}$$

In addition, the wet air mass flow rate (q_{mwet}) measured by the orifice meter was compared with the dry air mass flow rate (q_{mdry}) measured by the turbine meter. Equation (8) defines the % deviation of the indicated wet flow rate from the reference dry flow rate. Again, the equation of state for dry air was used to calculate the density of the wet air.

$$\% \text{ Deviation} = \frac{\left(q_{mwet} - q_{mdry}\right)}{q_{mdry}} \times 100 \tag{8}$$

Figures 4–8 show the results of the water entrainment experiments for the 20.32 cm (8-inch) orifice meters with 0.5 and 0.7 beta ratios. The deviations of the discharge coefficient (Equation 7) and mass flow rate (Equation 8) are plotted as a function of the orifice Reynolds number for different water injection rates. The water injection rates are expressed in terms of mass flow rate ratios and are therefore dimensionless (see Equation 5).

Orifice Meter at 0.7 Beta Ratio

Figure 4 shows the discharge coefficient deviation (Equation 7) caused by liquid entrainment in the orifice meter at a beta ratio of 0.7. The water injection rate varied from a mass ratio of 0.000196 to 0.0208 over the orifice Reynolds number range form 4 to 9 million. A flow deviation plot is also presented in Figure 5 to show the effect of liquid entrainment on flow rate measurement. Test results at 0.7 beta ratio show that the flow rate deviation becomes increasingly negative with increasing mass ratio and Reynolds number, reaching an extreme of -1.7%.

When measuring wet natural gas in the field, the amount of liquid entrainment in the orifice meters is generally not known and the dry gas properties are used in the calculations even though the fluid was wet. It is also interesting to note that if density and viscosity corrections are made for the small amount of water added in the air in the flow calculations, the deviation do not change significantly. It was observed that the low flow readings were due in part to the lower differential pressure measurement when water was added to the flow.

In order to estimate the measurement uncertainty of entrained liquid in orifice meter measurements, data points are plotted in three mass ratio ranges, <0.0006, 0>, <0.02, 0.0006> and <0.02, 0.002>, as shown in Figure 6. A linear equation was fitted over the mass ratio range to illustrate how measurement bias in wet gas flow measurement can be estimated. It is not, however, the intention of this study to develop a model or best correlations to predict small amounts of liquid entrainment effects on orifice flow measurement. The results show that when the mass ratio was less than 0.006, flow rate measurement deviation was within -0.5%. However, when the mass ratio was greater than 0.002, the flow rate measurement deviation changed from -0.5% to -1.7% with increasing Reynolds numbers. Higher pressure tests conducted at CEESI also confirm earlier low-pressure test results published by the author.[13]

Orifice Meter at 0.5 Beta Ratio

Seven series of tests from mass ratio of 0.0005 to 0.0187 over the orifice Reynolds number range from 4 to 9 million were conducted. Figure 7 shows the discharge coefficient deviation (Equation 7) and Figure 8 presents the flow rate deviation caused by liquid entrainment in the orifice meter at 0.5 beta ratio. Unlike the orifice meter at 0.7 beta ratio, liquid entrainment tests at 0.5 beta ratio show less shift for the discharge coefficient and flow rate. Test results indicated the deviations are within ±0.5%, as shown in Figures 7 and 8.

CONCLUSION

The effect of liquid entrainment on the accuracy of orifice meters was systematically studied under controlled conditions at a flow calibration facility. The following conclusions were drawn:

1. The flow measurement uncertainty was higher at wet conditions when a small amount of liquid was entrained. Orifice meters undermeasured wet gas flow rate with increasing beta ratio and Reynolds number. Up to a 1.7% lower flow rate measurement was detected at 0.7 beta ratio.

2. Orifice meters performed better at 0.5 beta ratio when a small amount of liquid entrainment was presented. However, for best performance, entrained liquid should be removed upstream of the orifice meter.

3. High-pressure air/water tests confirmed natural gas orifice meter performance data collected from the field and low-pressure air/water tests.

ACKNOWLEDGMENT

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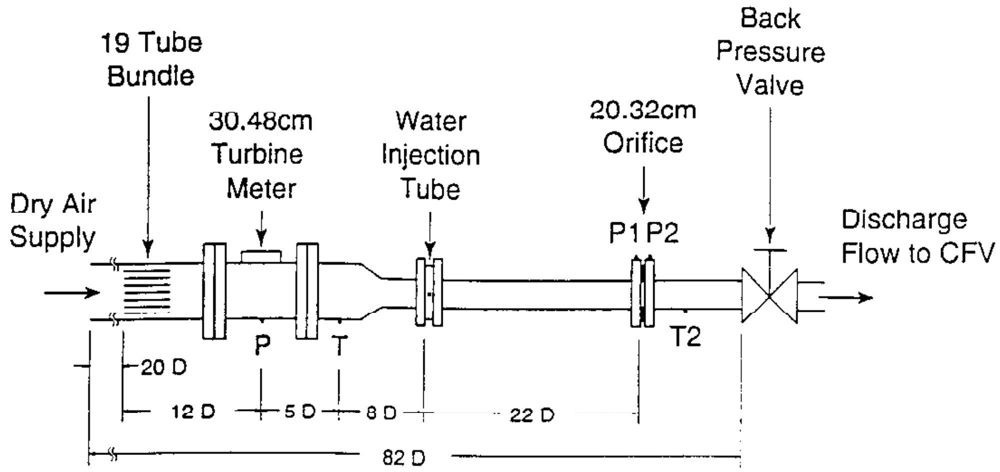

Figu 1. Flow Test Schematic

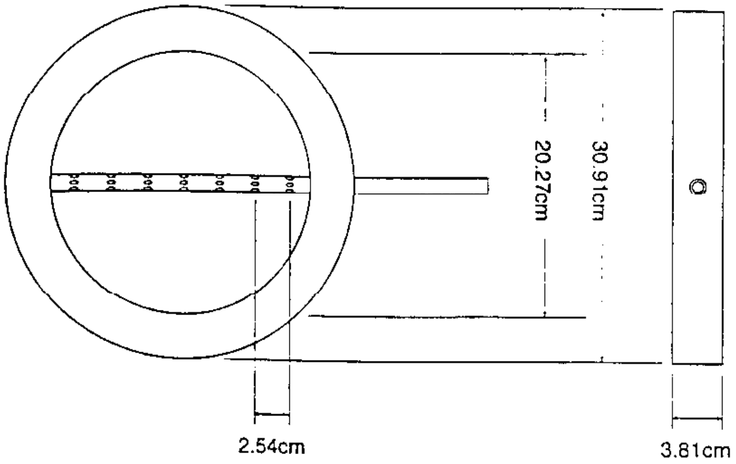

Figure 2. Water Injection Tube and Holder

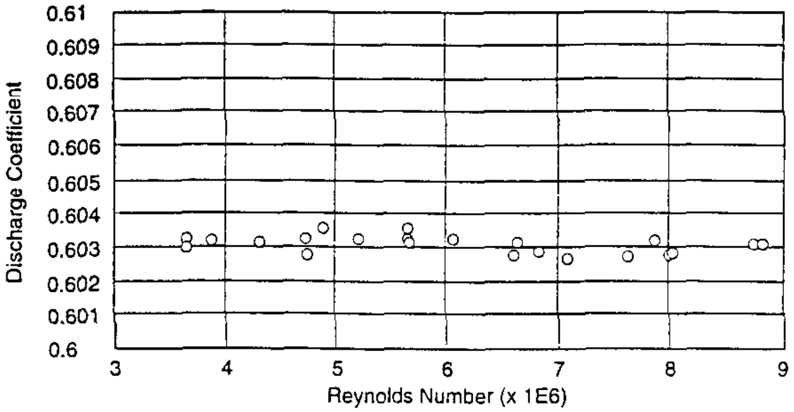

Figure 3

20.32 cm Orifice Meter Calibration Curve at 0.5 Beta Ratio

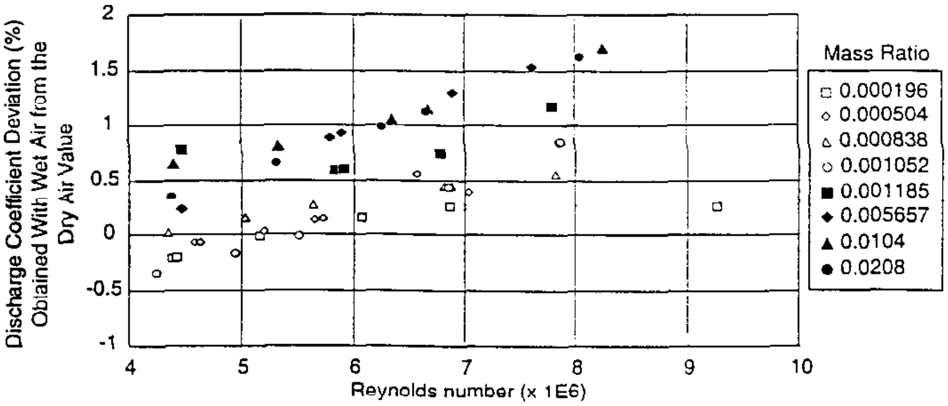

Figure 4

Effect of Liquid Entrainment on a 20.32 cm, 0.7 Beta, Orifice Meter--Discharge Coefficient Deviation

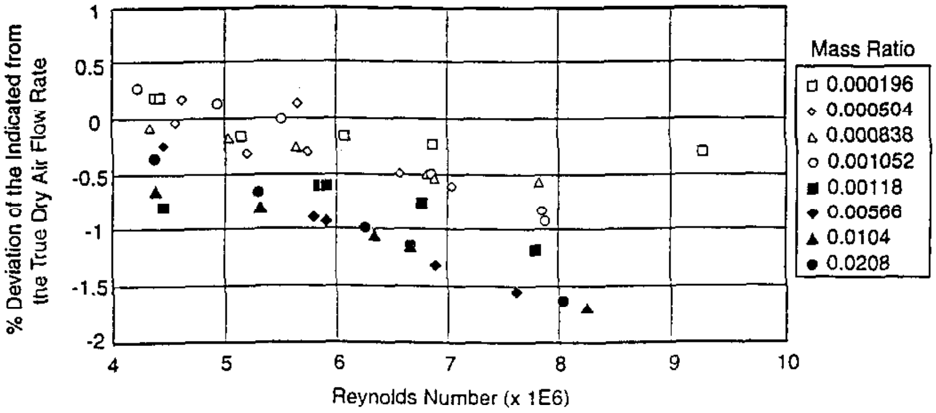

Figure 5

Effect of Liquid Entrainment on a 20.32 cm, 0.7 Beta, Orifice Meter--Flow Rate Deviation

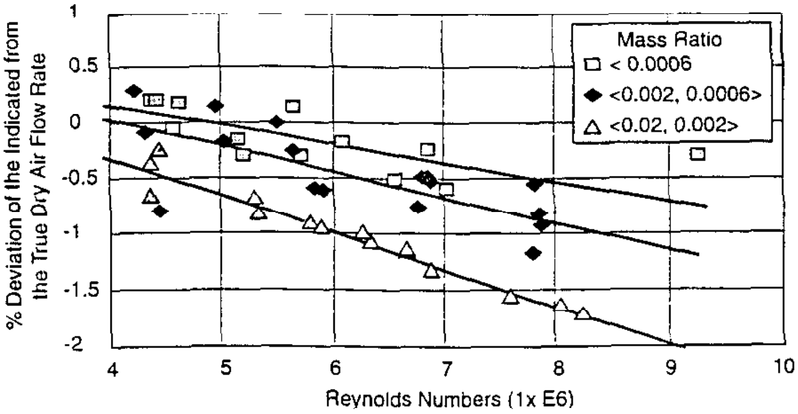

Figure 6

Effect of Liquid Entrainment on a 20.32 cm, Beta=0.7, Orifice Meter--Flow Rate Deviation

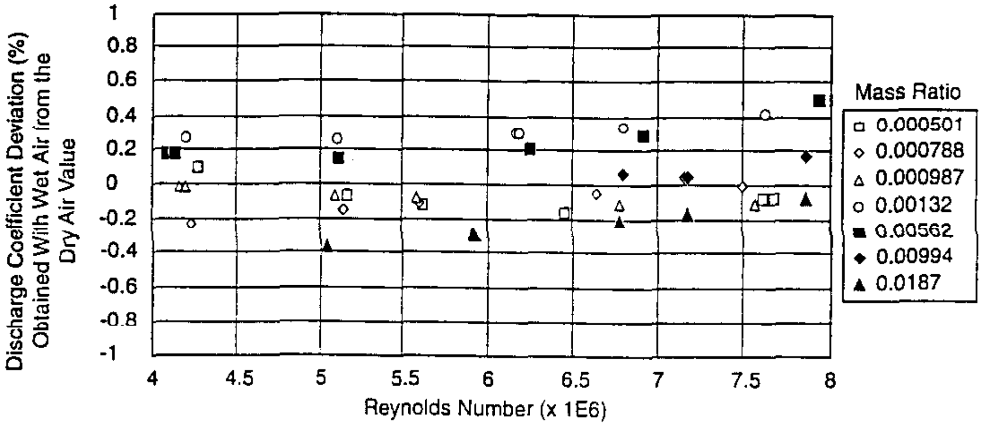

Figure 7

Effect of Liquid Entrainment on a 20.32 cm, Beta=0.5, Orifice Meter--Discharge Coefficient Deviation

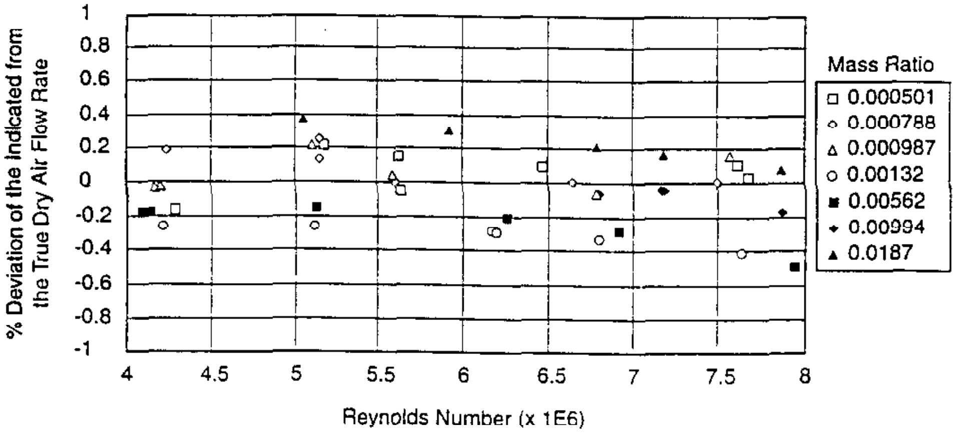

Figure 8

Effect of Liquid Entrainment on a 20.32 cm, Beta=0.5, Orifice Meter--Flow Rate Deviation