Proceedings of the FEDSM2000
2000 ASME Fluids Engineering Conference
June 11-15, 2000, Boston, USA

FEDSM2000 - 11107

EXPERIMENTAL INVESTIGATION OF THE INSTALLATION EFFECTS ON THE VENTURI FLOWMETER PERFORMANCE

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ABSTRACT

The sensitivity of flow meters to their operational conditions continues to be a source of concern to both flow meters manufacturers and users. This paper presents the results of an experimental investigation on the effects of non-standards operating conditions (approaching flow and internal geometrical irregularities) on the accuracy of the Venturi flow meter. The results showed that the error caused by such non-standards operating conditions can be very important which would lead to significant economical losses.

INTRODUCTION

In recent years there has been a considerable development of sophisticated flow meters. It is estimated that at least 100 flow meter types are commercially available, and new types are continually introduced. According to Paik (1994), the world flow meter market size in 1998 was about 1.9 10^9 US Dollars. The estimated annual growth would be about 6.6 percent. When flow meters are classified into technology, differential pressure flow meter will be the most widely used one in industry by having 25 percent of the market share. This group of flow meters would include orifice plates, Venturi meters and point measurements velocity devices, such as the Pitot-static tube. These devices are described in the standards ISO 5167 (1991). The proven record of differential pressure flow meters for reliable, repeatable monitoring flow measurements has made them very popular especially in the oil and gas industry. Du to the large volumes transported through pipelines, small differences between receipts and deliveries may cause some problems between suppliers and clients. This is of particular interest to large companies such as the Algerian petroleum company SONATRACH which in 1997, its transmission division recorded receipts of 56 10^9 m^3 of gas. The quality of gas measurement receipt and major delivery points distributed through 13000 km of pipeline is very important. Design, operation and maintenance decisions must be cost justified. Therefore it is necessary to understand how equipment condition, station design, and operational parameters can all affect metering accuracy.

For custody transfer of valuable fluids, accurate flow measurements are required. Various research efforts have been made in order to improve the performance of flow meters. A fundamental understanding of the effects of flow meter operational conditions upon the discharge coefficient is necessary to reduce or to eliminate installation effects which decrease the accuracy of flow metres. In the recent years, concentrated research work in USA (Mattingly, G.E., and Yeh, (1991, 1996), Spitzer, (1993), Morrison et al.(1992), Morrow et al. (1991), Brennan et al. (1991)), in the U..K (Reader-Harris and Keegans (1986) and Laws et al. (1994)), in Canada McConaghy et al. (1989) and in France (Gajan et al.(1991)) has been devoted to study experimentally and computationally the installation effects upon differential pressure flow meters. Most of these studies evaluated the effect upon the discharge coefficient of changing the location of flow conditioner with respect to the orifice meter.

Among the differential pressure flow meters, the Venturi meter has a long and distinguished history and still dominates the flow measurements scene despite the development of more sophisticated flow meters. The Venturi meter was invented by Clemens Herschell in 1887, a graduate of the Harvard University. Since then, the Venturi has been used in the oil and gas industry especially where energy conservation is an important consideration in large pumped flows. Its low head loss, comparatively to the orifice flow meter, continues to be one of its major advantages. It has also been used for slurry and two-phase flows. The standards ISO 5167 stated that the effect of upstream pipe fittings on the performance of the Venturi is much reduced from the orifice requirements. This is due to the flow stability in the meter, which results from its smooth geometry. An additional advantage of the Venturi meter might be seen as the high value of the discharge coefficient, which means that the performance approaches the theoretical value. This in turn would suggest a more reliable precision of the venturi meter. In the open literature, the Venturi flow meter was not considered sufficiently. Experimental work presented by Arnberg et al. (1973) considered the determination of the discharge coefficient, C_d, with different upstream pipe fittings. In an effort to determine how operational conditions affect the accuracy of Venturi flow meter and to determine their effects upon the discharge coefficient, the authors undertook a research programme sponsored by the National Agency of Research and Development (ANDRU), Algeria. The first part of the programme, which was presented by Aichouni et al. (1996), consisted of an experimental study of the effect of highly distorted flow conditions on the accuracy of a venturi flow meter. The results showed that highly distorted flow condition could cause important error in the meter reading. The magnitude of the meter error was found to depend on the flow Reynolds number. Changes of flow meter geometry due to damages, liquid and solid build up and meter surface roughness can all affect measurement accuracy. The impact of these effects on the Venturi meter reading was considered experimentally in the second part of the research work and presented by Aichouni et al. (1998). In the present paper we shall discuss further the experimental results and present an analysis of the effects on the meter performance.

EXPERIMENTAL FACILITY AND PROCEDURE

The basic experimental facility is presented in figure 1. It consists of a long PVC pipe with an inner diameter of 25mm. The test section (Venturi type flow meter) is an accurately machined perplex duct of varying circular cross section supplied by the Armfield Inc. UK. The geometry of the test section was consistent with the ISO 5167 design requirements. The converging section is 21° angle and 56.95 mm long. The diverging section has an angle of 15° and a length of 58 mm. The Venturi test meter was mounted in the long pipe (at the fully developed flow condition) using union couplings, which are leak proof. The static pressure can be measured simultaneously from wall pressure tappings at 6 sections along the Venturi meter. The pressure tapings were connected to a multi tube manometer. Water is pumped through the pipe section. The flow rate can be determined from the measured differential pressure along the Venturi and directly measured from a constant volume tank system. The discharge coefficient was obtained from the measured flow rates with an estimated uncertainty of ±0.5 percent which agree with the standards tolerated error.

In the first part of the experimental programme, which concerns the study of the effects of disturbed flow conditions upon the flow meter performance, the Venturi meter was first installed in the fully developed flow condition at some 100 pipe diameters downstream of the pipe entrance. Then, three different flow velocity distortions were created at the inlet of the Venturi meter by inserting shaped gauze screens. The conditions were a uniform flow (obtained using a uniform porosity grid), a jet type distortion and a wake type distortion using shaped gauze screens. A schematic representation of the three velocity distortions is presented in figure 2. These velocity conditions greatly exaggerate the maldistributions normally present in industrial flowmeter runs.

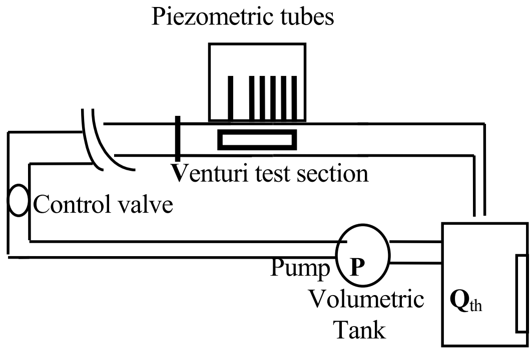
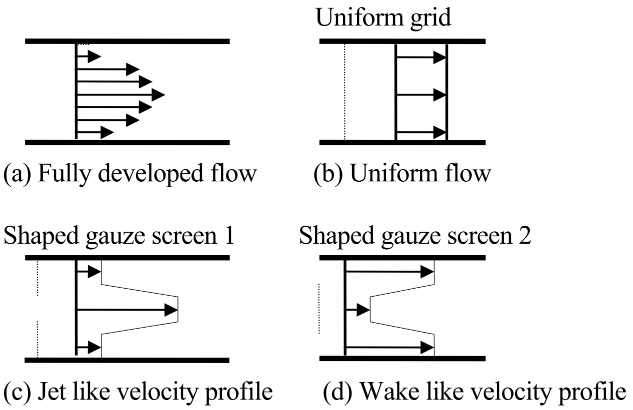


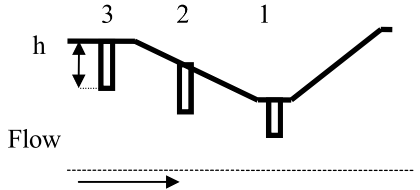
Figure 1 - Schematic of the test facility



(a) Fully developed flow (b) Uniform flow

(c) Jet like velocity profile (d) Wake like velocity profile

A – Upstream flow conditions



B - Geometrical irregularities in the Venturi

Figure 2 - Schematic of the test flow conditions

Geometrical changes of the internal meter surface were simulated using plain washers. The washers with sizes of (0.95, 1.90 and 2.60 mm) were inserted at different locations of the converging section of the meter as shown in figure (2-B). The measurements were made at Reynolds number ranging from 4 to $20x10^3$.Using this test facility, the various flow conditions (inlet velocity profiles and internal geometrical irregularities) were generated with the Venturi meter in place and the resulting pressure drop across the meter recorded. From the measured flow rates, Q, the discharge coefficient, C_d, was calculated using the measured pressure drop, ΔP, the fluid density, ρ, and the Venturi meter geometry following the recommendations of the ISO5167.

RESULTS AND DISCUSSION

The purpose of the experimental study was to determine the relative change of the Venturi meter reading due to :

a) Distorted approaching flow conditions and
b) abnormal flow meter internal conditions.

In the first part of the programme, three velocity profiles were generated by the shaped gauze screens. This technique has been used by Laws and Aichouni (1990,1992) to create highly distorted flows in circular pipes. These velocity conditions, shown schematically in figure (2-A) greatly exaggerate the maldistributions normally present in industrial flowmeter runs. They were used to demonstrate the cause and effect of axisymmetric distorted velocity profiles. The velocity distortions range from a jet profile with high centreline velocity and slower velocities near the pipe wall to a wake velocity profile with low centreline velocities. In the second part of the work, internal geometrical irregularities were simulated using plain washers which were inserted into the meter at three different positions.

The flow rate was first measured under fully developed flow condition and clean internal meter geometry. Then abnormal flow conditions were created and the corresponding flow rate was measured. The flow rate error and the discharge coefficient shift were determined to see the effect of the installation effects on the meter reading. According to the standards ISO 5167 the flow rate was determined from the differential pressure measured through the Venturi meter. The discharge coefficient was determined as the ratio of the measured flow rate to the true flow rate measured from the constant volume tank. The percentage shift in the discharge coefficient was determined from the relationship :

$$\Delta C_d = \left(\frac{C_{d0} - C_d}{C_{d0}} \right) x100 \qquad (1)$$

Where C_{d0} represents the discharge coefficient measured under standards conditions (clean meter with no obstacles at fully developed flow condition) and C_d being the discharge measured under non-standards operating conditions.

The flow through the Venturi meter illustrates a well-behaved nature of a flow when the area changes blend smoothly from the converging section to the diverging one. In the converging section of the meter, the flow accelerates due to the smaller area and the pressure decreases and vice versa in the diverging section. Such flow behaviour is dictated by the Bernoulli and the continuity equations which describe respectively the energy and the mass conservation principles of the fluid flow. Though the flow nature in the meter seems to be simple in the case of a clean internal surface and an upstream fully developed flow condition, the general flow field can be affected by any changes in the approaching flow and the meter internal geometry. Hence the determined flow meter parameters can be greatly affected by non-standard operating conditions.

Effect of upstream flow conditions

The effect of the flow conditions on the percent change of the discharge coefficient, ΔC_d (%), is shown in figure 3. The ΔC_d (%) varied from ±7.5 % for the jet distortion type flow to ±0.5 % for the wake distortion. The general trend is that the C_d shift is much higher for lower Reynolds numbers and tends to decrease as the Reynolds number increases. This observation holds for the three flow conditions considered here. This figure indicates that the ΔC_d (%) decreases in a linear manner with the Reynolds number, R_e. This finding is in agreement with results presented by Laws et al. (1994) who found similar variation of ΔC_d(%) in the case of an orifice meter running under other flow conditions. The present results would be of great practical importance, since it suggests that for a differential pressure flowmeter which operates under conditions other than the fully developed condition, the accuracy of the flow meter would be less affected for runs at high Reynolds numbers.

At a given Reynolds number, the results indicate that the pressure distribution along the Venturi meter depends on the approaching flow condition. For the case of the wake flow distortion type, the presence of higher momentum near the pipe wall and lower momentum at pipe centre, result in an increase of the pressure drop along the Venturi and hence to a decrease of the discharge coefficient. The greater amount of the momentum along the outer wall requires that more force be applied to accelerate the flow inward into the contraction of the meter. This additional force can only be supplied by the pressure gradient. Therefore, additional force equates to additional pressure drop along the Venturi meter. The lowest values of the percent change of the discharge coefficient, ΔC_d(%), as shown in figure 3, confirm this observation. The lowest momentum near the pipe wall and higher momentum at the pipe centre for the jet flow distortion caused a decrease of the pressure drop along the meter and an increase of the discharge coefficient resulting in variation of ±7.5 % of the percent change in the discharge coefficient, ΔC_d (%), for the most extreme case measured at a Reynolds number of $7x10^3$.

In the present study attempts were made to find correlations between the percent change of the discharge coefficient, ΔC_d (%), and parameters characterising the flow distortion such as the kinetic energy parameter α, the axial momentum parameter β, the turbulence parameter Ig and the Reynolds number. The coefficients α, β and Ig were determined from hot-wire measurements and CFD computations of the axial velocity and the turbulence intensity profiles at similar Reynolds numbers and presented by Aichouni (1992). The correlations between percent change in the discharge coefficient, ΔC_d (%), with the coefficients α, β and Ig were poor. Morrow et al. (1991) and Morrison et al. (1992) carried out experimental and numerical studies on the effect of distorted flow conditions upon orifice plates flow meters and tried to correlate their measured ΔC_d (%) with the axial momentum fluxes (mvr^n). Their results showed poor agreement for the higher order moments, while for the lower order moments the agreement was better.

Figure 3 – Percent Change of the Discharge Coefficient for Different Upstream Flow Conditions

Effect of internal geometrical irregularities

The percentage discharge coefficient error $\Delta C_d(\%)$ due to abnormal internal conditions is presented for various tests as a function of the flow Reynolds number in figures 4 (a, b, c and d). The position of the obstacles has a great effect on the magnitude of the error. Error ranging from 20 to 30 percent was obtained for the maximum height of the obstacles placed near the pressure taps (positions 1-3 and 1-2-3). At a given Reynolds number, the error decreases when the size of the obstacle decreases. For all the obstacles the error decreases with the flow Reynolds number. This is in good agreement with the early observation made in the previous section.

In order to search for correlation between the percent change of the measured discharge coefficient $\Delta C_d(\%)$ and parameters characterising the flow meter operational conditions, a statistical approach based on the experiment design methods described in Bailey (1995) has been used. This approach allowed to study the effect of the different operational parameters on the meter reading (the number, the size of the geometrical irregularities and the flow Reynolds number) respectively. The results of the analysis show that the variation of the meter error is non-linear with the parameters. An analytical model has been obtained from the analysis to represent $\Delta C_d(\%)$ as a function of the Reynolds number, the number and the size of the obstacles. The model can be expressed as :

$$\Delta C_d(\%) = A_0 + A_1 Re + A_2 h + A_3 n.h + A_4 Re.h.n \qquad (2)$$

Here A_i are the coefficients of the model, determined from the experimental data. In the model given by equation (2), only the significant coefficients were taken. Small magnitude coefficients were dropped. From the magnitude of the coefficients, which are ranged according to their significance, it is suggested that the flow Reynolds number and the size of the obstacle are the most important parameters that influence the meter reading error. The proposed model confirm the early observation on the meter reading dependency on the flow Reynolds number.

CONCLUSIONS

The present experimental study shows that the operating flow conditions have significant effects on the Venturi flow meter performance. Highly distorted flow conditions can cause errors up to ±7.5 percent on the discharge coefficient. These effects can be due to the flow instability in the meter caused by the approaching flow distortions. Errors up to± 30 percent can be registered by the meter if high solid obstacles build up near the pressure taps. These can cause dramatic changes of the flow development and the pressure field.

In the light of the present experimental study, in order to avoid any measurement errors and as stated by the standards, the flow meter should be run under fully developed flow condition and kept clean and free of all extraneous material at all times. It is the author's opinion that more research efforts should be continued to quantify the installation effects upon industrial flow meters. Numerical predictions are undergoing to carry out the investigation.

Figure 4 - Percentage Change of the Discharge Coefficient for Different Geometrical Irregularities

ACKNOWLEDGMENT

The Sponsoring of the present work under Contract Number OC399701 by the National Agency for Research Development (ANDRU), Algeria, is greatly acknowledged by the authors.

NOMENCLATURE

C_d	Coefficient of discharge
D	Pipe diameter
h	Height of the obstacles
n	Number of geometrical obstacles
Q	Discharge (Flow rate)
R_e	Reynolds Number ($R_e = \rho U_m D / \mu$)
U_m	Flow mean velocity
μ	Fluid absolute viscosity
ρ	Fluid density

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