The use of CAD System for Improving Flow Conditioner Design to Reduce Installation Effects On Orifice Metering

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Abstract: The sensitivity of differential-pressure flow meters to the quality of the approaching flow continues to be a cause for concern to flowmeter manufacturers and users. Distortions to the approaching velocity profiles generated by pipe fittings and installations located upstream of a flowmeter, can lead to considerable errors in flowmetering. This cannot be ignored because of the likely cost and process efficiency implications. This paper describes the effects of various entrance flow velocity profiles on the performance of an orifice flowmeter with and without flow conditioning. Asymmetric swirling velocity profiles were generated by a ball valve. These caused significant shifts to the meter's calibration. The use of a vaned-plate flow conditioner, consisting of six vanes attached to a 70% porosity plate, greatly improved the performance of the meter. Thus, the device can be used as part of a flowmetering package that will have considerably reduced installation lengths. The less-sophisticated NEL plate proved to be a good flow straightened, i.e. a good swirl remover, but was not an efficient flow conditioner.

Keywords: orifice meter; discharge coefficient; flow measurement; velocity profile; flow conditioning; turbulence; swirl.

NOTATION

C_d	coefficient of discharge
R	pipe radius (m)
Re	Reynolds number
d	diameter of holes in flow conditioner (m)
D	pipe diameter (m)
U	local axial fluid velocity (ms^{-1})
U_m	mean axial flow velocity (ms^{-1})
Y	radial distance (m)
Z	axial distance along pipe
ΔC_d	discharge coefficient error
ΔP	pressure drop (Nm^{-2})
β	orifice-pipe diameter ratio
θ	swirl angle

1 Introduction

Measurement of flow is necessary to (i) establish ratios of materials needed in continuous process; and (ii) determine the distribution of materials for cost control and other efficiency studies; in such cases high accuracy flowmetering is usually required. The ability to accurately measure the flowrate of a fluid in a closed conduit is of major concern and vital importance in many industries.

The custody transfer of oil and gas, the metering of water and chemicals, and the transport and distribution of fluid mixtures in the process industries (including food manufacturing) are some areas in which mass and volume flow rate are important. Errors in flow measurement can have large cost and /or efficiency implications. For example, losses due unaccounted-for natural gas and custody transfer metering stations can amount to millions of pounds, and because of the large volumes involved in these transfers, even small improvements in flowmetering accuracy will produce large savings. Flowmeters form one of the few classes of instrument that tend to be harder to use than to manufacture. Manufacturers usually go to great lengths to develop accurately machined flowmeters and to produce accurate calibration charts. This, however, is of limited benefit if the instrument is not properly installed.

The quality of the installation is as important for optimum flowmeter performance as the quality of construction. Most flowmeters are affected by the flow regime in which they operate, but, at the time of manufacture they are tested and calibrated under the ideal conditions of fully developed, axisymmetric pipe flow; that is free from swirl and pulsation Such conditions are dictated by the test standards (e.g. [1], [2]). Standards such as [1] define a satisfactory flow as one which has a swirl angle of less than degrees, and the ratio of the axial velocity at any point on a given cross-section of the flow to the maximum axial velocity on that cross-section is within 5% of the corresponding ratio in fully developed flow as measured in the same pipe after 100 pipe diameters of development length. In practice, however, flowmeters are usually installed in rigs where the flow may not be fully developed and is subject to significant swirl. This is because flowmeters often, and unavoidably, have to be located in plant pipework downstream of pipefittings such as bends, valves, reducers and expanders. These produce distorted velocity profiles and varying degrees of swirl at the inlet to the meter. A swirling flow is characterised by a vortical motion, which is superimposed on the basic axial flow through the pipe. The tangential velocity component is usually of a magnitude comparable to the mean axial velocity of flow. Once established, turbulent swirling motion is most persistent and the angular momentum associated with it requires great lengths of straight pipe to decay, typically 60 pipe diameters to reduce to one tenth of its original level. Such flow conditions will effect the calibration of flowmeter by changing its discharge coefficient from that determined from the ideal flow conditions recommended by the test standards. This will result in the accuracy of the flowmeter being impaired. The resulting errors in flow measurement can be a major concern in those industrial processes where accuracy and precision are crucial. For best accuracy, a flowmeter needs to be presented with an axisymmetric, fully developed velocity profile with zero swirl. Lengthy runs of straight pipe and straightening vanes will produce these conditions. The standards on flowmetering specify the lengths of straight pipe which should be incorporated upstream and downstream of a metering device for the published characteristics to apply (e.g. [1]). This, however, will give a higher installation cost and a greater space requirement. Alternatively, upstream disturbances can be attenuated by using flow straighteners and/or flow conditioners to control the quality of the flow approaching the metering device. A flow straightener is a device which eliminates swirl from the flow but has little or no effect on thee velocity profile. A flow conditioner, on the other hand, is a device that not only eliminates swirl but also produces a repeatable downstream velocity profile, irrespective of upstream flow disturbances. The combination of a flow conditioner and flowmeter into a single compact package offers an elegant, cost-effective approach to safeguarding flowmeter performance installations. A fundamental understanding of the approaching velocity profiles and their effects on the discharge coefficient of metering device is essential knowledge for the rational design of a flow conditioner-meter package that minims installation effects. Research work in the USA ([3];[4]), in the UK ([5], [6], [7,8]),and in France ([9] has a reported a number of experimental and computational studies of installation effects on orifice flowmeter performance. Most of these studies investigated the effect on the discharge coefficient of flow conditioner location with respect to the orifice meter. It was found that when the mean velocity profile upstream of the orifice had a deficit on the centreline and higher velocities at the outer edges of the pipe, the pressure drop across the orifice was greater than for fully developed flow. Furthermore, it was suggested that there was a correlation between the resulting shift in the discharge coefficient and the axial momentum flux of the approaching flow. In a recent study, [10] conducted an investigation into the effects of various entrance flow distortions on the performance of a venturi flowmeter .The venturi was first installed and evaluated 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 meter:(i) a uniform flow obtained by inserting a uniform porosity grid; (ii) a jet-type velocity profile and (iii) a wake-type velocity profile, achieved by means of shaped gauze screens. The measurements were made at Reynolds number in the range 4000 to 20000. The flow distortions led to a deterioration in the discharge coefficient of up to 70%, reducing to about 1% at the higher Reynolds numbers. This suggests that, at high Reynolds numbers, the performance of the1venturi meter is less affected by upstream flow distortions. In this paper, the effects of various entrance flow velocity profiles, generated by a ball valve on the accuracy of an orifice meter are investigated. The performance of the flowmeter is also assessed when coupled with a vaned-plate flow conditioner and an NEL-plate flow conditioner.

2 Experimental

2.1 Air flow rig

The test configuration used is shown in Fig. 1. The closed circuit rig was constructed from a 0.103 m diameter pipe. The flow was powered by a 22 kW induction motor driving a centrifugal fan. The air flow rate was controlled by a valve installed in the return part of the loop. A water heat exchanger was used to keep the air temperature constant. The orifice plates studied were of standard geometry and had pressure tappings one D upstream and D/2 downstream, where D is the pipe diameter. The test section was preceded by a ball valve which was used to generate different upstream flow profiles as illustrated in Fig. 2. When used, the flow conditioner was positioned at an axial distance Z=3D downstream of the exit plane of the ball valve. The upstream pressure tapping of the orifice plate was situated at Z=3D downstream of the flow conditioner. The ball valve was preceded by a 16:1 area-ratio Bloomer contraction section. The contraction produced a low turbulence inlet flow with a relatively uniform velocity profile and a very thin boundary layer. The overall length of the test section was approximately 110D. The pressure drop across the Bloomer contraction was used as the primary means of flow measurement. The orifice discharge coefficient was determined from the ratio of the real flow as determined from the pressure drop across the contraction $\Delta P_{1-2,}$ and the ideal flow as determined from the pressure drop across the orifice plate ΔP_{3-4} , i.e.

$$C_d = \sqrt{\frac{\Delta P_{1-2}}{\Delta P_{3-4}}} \tag{1}$$

Where the indices correspond to the pressure tappings shown in Fig. 1. The error involved in the determination of C_d was within ±0.05%.

2.2 Flow conditioners

Two flow conditioners were studied in conjunction with the orifice meter.

2.2.1 Vaned-plate flow conditioner

The vaned plate was introduced and described by [7,8]. It consists of 6 vanes attached to a 70% porosity plate and is shown in Fig. 3. The holes are arranged so that a central hole of diameter d_1=0.224D is surrounded by an inner ring of 6 holes having equal diameter d_2=0.2213D, and an outer ring of 12 holes of equal diameter d_3=0.177D. The vanes are placed on the upstream side of the plate with short fins attached to the back of the plate to give structural strength on the assembly. This flow conditioner incurs a pressure loss of about 0.9 velocity heads[9]. This head loss is largely dictated by the porosity of the plate; for example, a porosity 60% would lead a head loss of 1.8 velocity heads [9].

2.2.2 NEL-plate flow conditioner

The NEL flow conditioner is shown in fig. 4 and was introduced by [11]. It consists of a Single perforated plate with 16 holes in an outer ring, 8 holes in an inner ring, and 4 holes arranged In a square at the centre. The NEL plate is recommended to have d_1 = 0.1D, d_2=0.16D, and d_3=0.12D, giving a porosity of 47.5% and a pressure loss of about 2.9 velocity heads. There is limited scope for reducing the pressure loss by increasing the plate porosity, without the central 4 holes interfering with the holes in the inner ring.

2.3 Radial velocity measurements

The radial velocity profiles were determined using a pitot rake. The instrument was designed on the principle of the equal area method. Here, the pipe cross section is divided by concentric circles into a number of zones of equal area. The rake tubes were located symmetrically about the centreline at the mid-point of the equal area annuli. However, because this arrangement would yield insufficient information in the core region of the pipe, extra tubes were added to the rake to cover this area. Thus, of the 27 tubes of the rake, 21 were located on the equal area principle and 3 additional tubes on each radius were added near to the pipe centreline. The pitot rake enabled measurement to be taken at 27 points along the pipe diameter, the nearest point to the wall being at distance of 3.5 mm. The maximum possible error in measurement velocity by such a method was ±0.6%.

2.4 Turbulence measurements

Axial turbulence intensity measurements were made using a single hot-wire-anemometer probe made by DISA. The probe was positioned in the test rig using a radial traversing mechanism incorporating a linear scale which allowed the radial position of the probe to be adjusted to an accuracy of ± 0.5.mm. Since the anemometer, four-arm, resistive bridge must be accurately balanced use, the probe circuit was allowed sufficient time to warm up and stabilise before performing measurements. A typical r.m.s error on the calibration curve was around ≈ 0.1 m/s.

2.5 Swirl measurements

Swirl angle measurements were carried out using a five-hole Conrad yawmeter. Such measurements were acquired at different stations upstream and downstream of the flow conditioner used, in order to assess its effectiveness in removing swirl generated by the ball valve. The swirl was determined at a number of radial locations by traversing the yawmeter through the pipe cross-section. Due to the design of traversing design and the swan-necked nature of the yawmeter head, it was not possible to traverse the whole pipe diameter so that only the far radius was covered. Thus, to explore the whole pipe diameter it was necessary to rotate the pipe through 180 degrees. The swirl was determined using a null-reading method. Initially, the yawmeter was placed at the required station along the pipe parallel to the pipe axis and facing the flow. In the presence of swirl, a pressure difference is created between the two tubes in the yawmeter which lie in the plane of flow but on opposite sides of the central tube. The instrument was about its axis from its initial reference position until zero pressure difference was obtained. Because the accuracy of the swirl values obtained using this measurement technique depended on the accuracy of the setting of the initial datum position, great care had to be exercised in setting the reference condition for the yawmeter. The yawmeter was positioned in a spare section of pipe with no flow approaching, and was carefully aligned so that its head lay along the pipe axis. This position was then taken as the zero setting for the yawmeter. The relative swirl angle along each traverse was measured to within ±0.5 degree uncertainty.

3 Results and discussion

3.1 Effects of upstream flow conditions on orifice meter performance

Experiments were conducted to determine the relative change in the orifice meter discharge coefficient when subjected to non-standard approaching flow conditions. Three different velocity profiles, as shown in Fig. 2, were generated by different valve settings based on flow area (fully open; 50% closed; 70% closed) upstream of the orifice plate (see Fig. 1). The effects of such distorted velocity profiles on three orifice plates were examined on the orifice-pipe diameter ratios of Beta = 0.5, 0.6, 0.7, over a wide range of Reynolds numbers from 0.33×10^5 to 2.5×10^5.

The percentage error in the discharge coefficient caused by distortions in the approaching flow was calculated using the following formula.

$$\Delta C_d = \frac{C_{d100} - C_d}{C_d} \times 100 \qquad (2)$$

Where C_{d100} is the calibration value of the discharge coefficient obtained when the orifice plate was positioned at Z=100D from the valve, where the flow is expected to be fully developed, and C_d is the value when plate was placed in its test position downstream of the valve, and was thus subjected to distorted inlet velocity profiles. The error on C_d caused by distortions in the approaching flow was, therefore, quantified in terms of its shift from the calibration value. The values of C_{d100} and C_d were evaluated according to equation (1). The values of C_d measured under the action of the ball valve were significantly different from the calibration values. As shown in Fig. 5, the absolute value of the error ΔC_d was as high as 1.5% for a fully open valve and up to 4% for 50% and 70% valve closures. These errors will lead to appreciable inaccuracies in flowmetering, hence the need to incorporate a suitable flow conditioner that reduces the effects of distortions in the approaching flow on C_d .

3.2 Performance of vaned-plate-orifice meter package

3.2.1 Characterisation of vaned-plate flow conditioner

The ability of the vaned plate (Fig. 3) to cope with distortions in the approaching flow was tested over a wide range of Reynolds numbers 6.9x10^4 to 2.19x10^5. The vaned plate was installed at a distance of Z=3D downstream of the ball valve and the time-averaged, radial velocity profiles were determined at two axial locations, Z=100D and Z=2.5D, downstream of it without the orifice meter in line. The valve closure was varied from fully open to 70% closed. The velocity profiles obtained at both locations were very close to being fully developed, regardless of the severity of distortion profile approaching the vaned plate, or Reynolds number. There was very little difference in the form or magnitude of the velocity distributions measured at the two locations downstream of the conditioner, as typified by Fig. 6. This therefore shows that the vaned plate is capable of producing high quality velocity profiles regardless of upstream flow conditions.

Axial turbulence intensity measurements were also made downstream of the vaned plate at axial distances Z=1.5D to Z=5.5D for different valve settings ranging from fully open to 70% closed. The turbulence intensity profiles were well behaved irrespective of the valve setting. The turbulence profiles measured at Z=2.5D for different valve settings, are compared in Fig. 7 to those corresponding to a fully developed profile, measured at Z=100D. It emerges that even at a relatively short distance downstream of the flow conditioner, the turbulence profile produced is reasonably close to fully developed one for all valve settings.

Swirl angle measurements were performed at an axial distance of Z=2.5D downstream of the vaned revealed maximum swirl angles across the pipe cross-section of 16 degrees and 29 degrees, respectively, As shown in Table 1, swirl angles downstream of the vaned plate were reduced to maximum of 1 degree for all valve settings. The vaned plate therefore appears to be an efficient flow conditioner. Firstly, the vanes play a major role in reducing swirl, and secondly, the graded perforated plate redistributes the flow, producing an almost fully developed profile within a short downstream settling distance.

	Y/D	**0.15**	**0.25**	**0.35**	**0.4**	**0.45**	**0.5**	**0.55**	**0.70**	**0.85**
Valve Fully open	**θ**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Valve 50% closed	**θ**	**1**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**1**
Valve 70% closed	**θ**	**1**	**0**	**1**	**1**	**0**	**0**	**0**	**1**	**1**

Table 1. Swirl angle values at Z=2.5D downstream of vaned plate

3.2.2 Effects of vaned-plate on orifice meter performance

The performance of the vaned plate-orifice meter package was tested with the flow conditioner installed at a distance Z=3D downstream of the exit plane of the ball valve, and a distance Z=3D upstream of the first pressure tapping of the orifice plate, see Fig. 1.

The use of the vaned plate to control the quality of the flow approaching the orifice meter led to minimal errors in the C_d values when compared to when the orifice plate was used alone. A typical plot of C_d as a function of Re is shown in Fig. 8 for Beta =0.7, and the correspon^{5}ding plot of delta C_d against Re is shown in Fig. 9. The values of C_d under distorted approaching flow conditions were only slightly lower than the calibration values, for all valve settings used. This confirms that the vaned plate coupled with an orifice meter would make an efficient flowmetering package. Furthermore, for different orifice plate sizes and for all valve settings used, the general trend was that ΔC_d decreased as Re increased. For an orifice plate with β=0.5, Delta C_d reduced from 0.24% to 0.09%, as Re increased from 0.3 x 10^5 to 0.6 x 10^5 for β=0.6, Delta C_d dropped from 0.23% to a value of 0.08%, as Re increased from 0.31x10^5 to 0.90x 10^5; and for beta=0.7, delta C_d reduced from 0.22% to 0.023%, as Re increased from 0.31x10^5 to 1.61x10^5. These results show that, when coupled to the vaned plate, the accuracy of the orifice meter improves at high operating Reynolds numbers as the error delta C_d reduces even further regardless of the orifice size used i.e. the beta ratio, and the severity of the distortions in the approaching flow. This is in line with similar findings by [10] and [12] concerning the performance at high Reynolds numbers of the venturi meter and the nozzle meter, respectively.

3.3 Performance of NEL plate-orifice meter package

3.3.1 Characterisation of NEL-plate flow conditioner

The procedure to characterise the performance of the NEL plate (Fig. 4) consisted of the same measurements as before, I. E. mean flow, turbulence, and swirl measurements in the same test rig. With the valve fully open, at Z= 1.5 D the velocity profile downstream of device had awake-like structure due to the blocked central portion of the plate. This mixed out quickly but a fully developed profile was not achieved until about Z= 4.5 D downstream of the plate. Setting the valve 50% closed generated an asymmetrical profile with a flatter central core than desirable. Similar profiles were produced with the valve 70% closed but with more pronounced asymmetry, as shown of poor quality. In all cases, longer pipe lengths were required to achieve profiles of similar quality to those produced by the vaned plate. Swirl angle measurements performed downstream of the NEL plate are reported in Table 2.

	Y/D	**0.15**	**0.25**	**0.35**	**0.40**	**0.45**	**0.50**	**0.55**	**0.70**	**0.85**
Valve fully Open	**θ**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Valve 50% Closed	**θ**	**1**	**1**	**0**	**0**	**0**	**1**	**0**	**1**	**1**
Valve 70% Closed	**θ**	**1**	**2**	**1**	**0**	**0**	**0**	**1**	**1**	**1**

Table 2. Swirl angle values at Z=2.5D downstream of NEL plate

Similar to the vaned plate, negligible swirl exists in the flow at Z=2.5D downstream of the NEL plate for all valve settings. This shows that the NEL plate is a good flow straightener. However, its ability to deliver an axisymmetric fully-developed velocity profile at short distances is very limited, and hence it is an efficient flow conditioner.

3.3.2 Effects of NEL plate on orifice meter performance

The possibility of using the NEL plate and the orifice meter as flowmetering package was tested under the action of the ball valve, to assess the magnitude of the likely errors involved. Although there was some improvement in the C_d values compared to using the orifice plate alone (see Fig. 5), the errors at low and moderate Reynolds numbers were still significant of the order of 1%, regardless of the valve opening. However, at $Re=6.5x10^4$, a dramatic improvement is observed in the performance of the package, as shown in Fig. 11. This phenomenon is not fully understood at present, but it is expected to be governed by the so-called mixing region which extends approximately to a distance Z=1.5D downstream of the flow conditioner. The reduction in the discharge coefficient error may be due to improved fluid mixing in this region at high Reynolds numbers. In order to fully understand the factors that control the performance of flow conditioning devices, and in particular the mechanism of swirl removal and turbulence production which are thought to be dictated by this mixing process, a detailed study of the mixing region would be needed.

4 Conclusions

The present study has shown that distortions in the approaching flow caused by pipe fittings upstream of an orifice meter can cause significant shifts in the meter's calibration, hence leading to considerable errors in flowmetering. These errors cannot be ignored as they can have important cost and/or process efficiency implications. The vaned-plate flow conditioner greatly improves the performance of the orifice meter and can be successfully used as part of a flowmetering package to reduce installation lengths. The error in the discharge coefficient is substantially reduced at low and moderate Reynolds numbers, with the discharge coefficient error becoming less than ≈0.1%.

The blocked central portion of the NEL plate gives an initial wake-like structure which mixes out quite quickly, but tends to lead to flatter velocity profiles than desirable. Although the NEL plate is a good flow straightener by being efficient at removing swirl, it requires a considerably longer settling length to produce the same downstream flow quality as the vaned plate. Hence, it would not be an efficient flow conditioner in short installations, especially at low and moderate Reynolds numbers.

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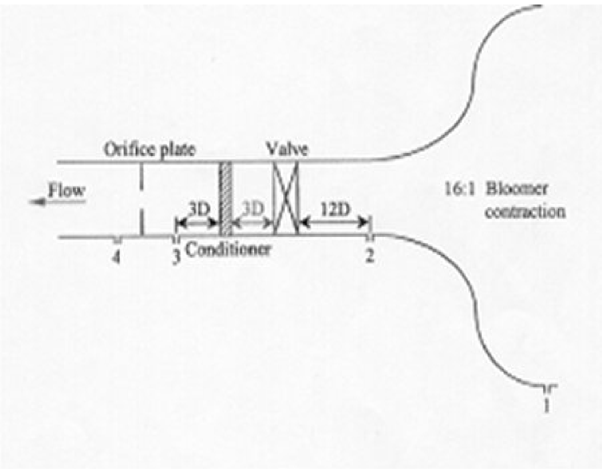

Figure 1. Inlet section of air flow rig with testing orifice Meter and a flow conditioner

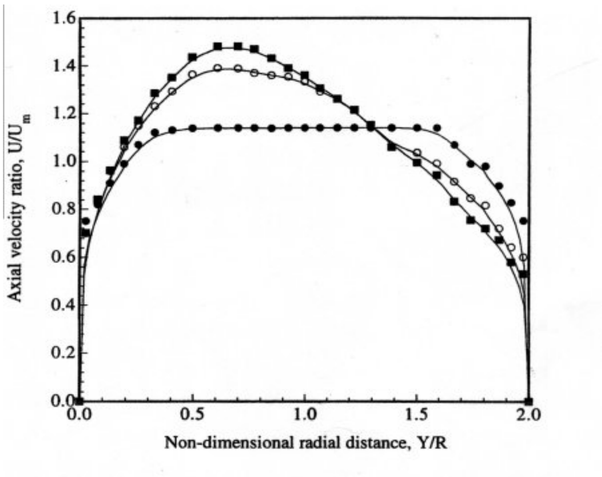

Figure 2. Mean velocity profiles generated by ball valves: valve fully open; o valve 50% closed, valve 70% closed

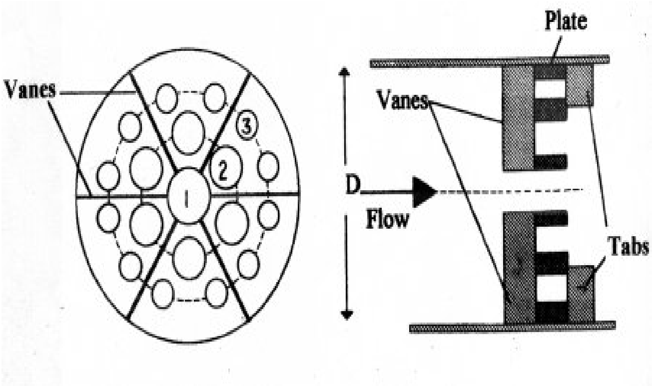

Figure 3. Vaned-plate flow conditioner: d1=0.224D; D2=0.213D; d3=0.117D

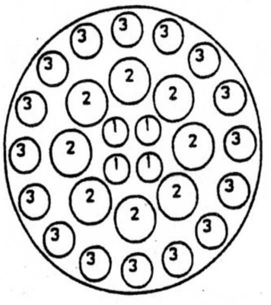

Figure 4. NEL-plate flow conditioner: d1=0.1A; d2=0.16D; d3=0.12D

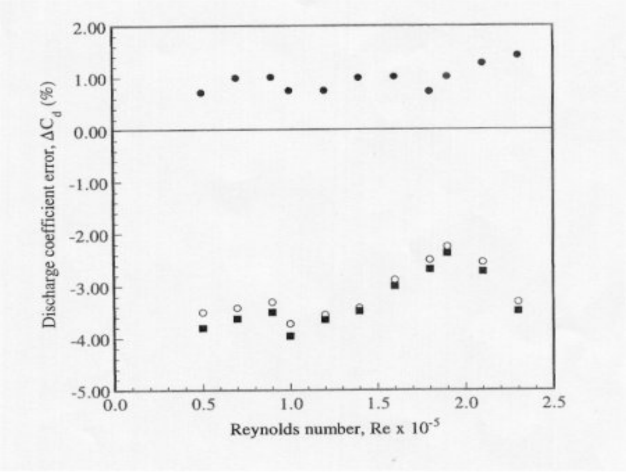

Figure 5. Discharge coefficient error without flow Conditioner in line, $\beta = 0.7$: valve fully open; o valve 50% closed; valve 70% closed

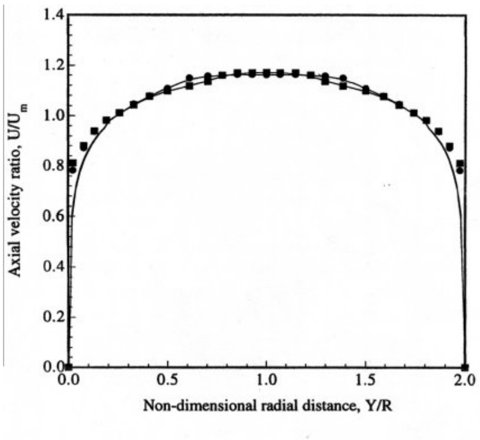

Figure 6. Mean velocity profiles downstream of vaned plate without orifice meter in line, for Re=2.19×10^3 : Z=100D valve fully open; o Z=2.5D valve fully opened; Z= 2.5D valve 70% closed

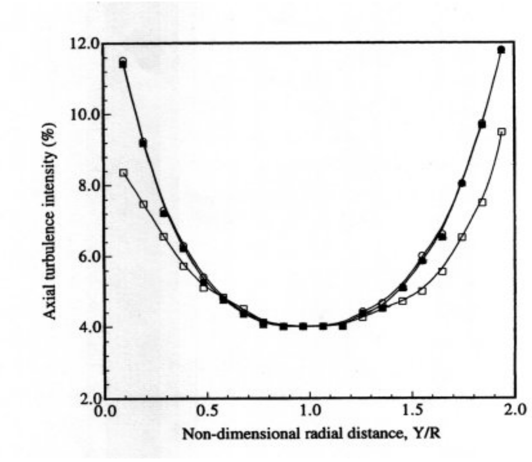

Figure 7. Axial turbulence intensity profiles downstream of vaned plate without orifice meter in line Z=2.5D: valve fully opened; o valve 50% closed, valve 70% closed.
Z=100D: valve fully opened

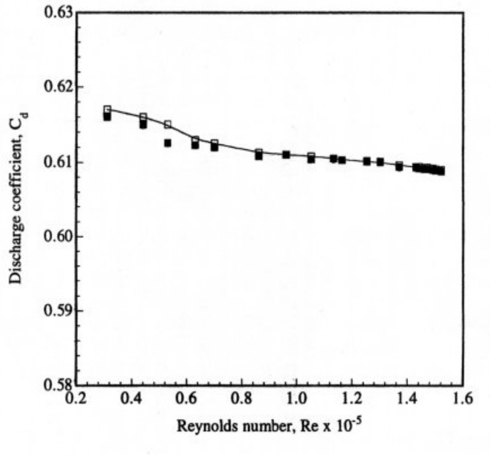

Figure 8. Discharge coefficient for vaned plate orifice meter package, $\beta = 0.7$: valve fully opened; o valve 50% closed, valve 70% closed; calibration

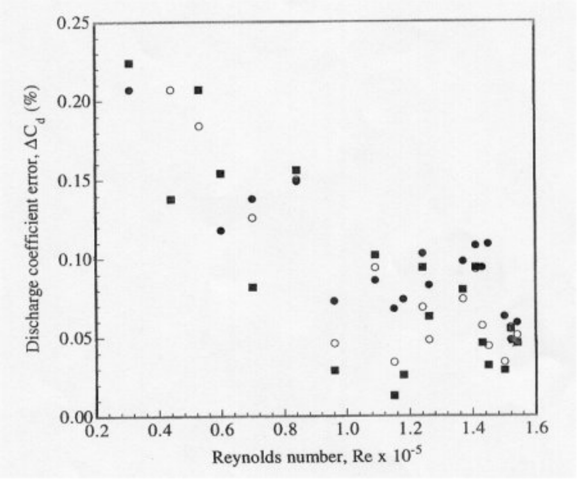

Figure 9. Discharge coefficient error for vaned plate Orifice meter package, $\beta = 0.7$: valve fully opened; o valve 50% closed, valve 70% closed

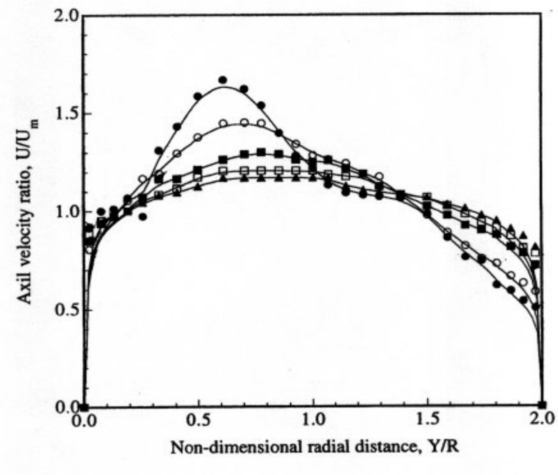

Figure 10. Mean velocity profiles downstream of NEL-plate with valve 70% closed: Z=1.5D; o Z=3.5D; Z=4.5D; Z=5.5D

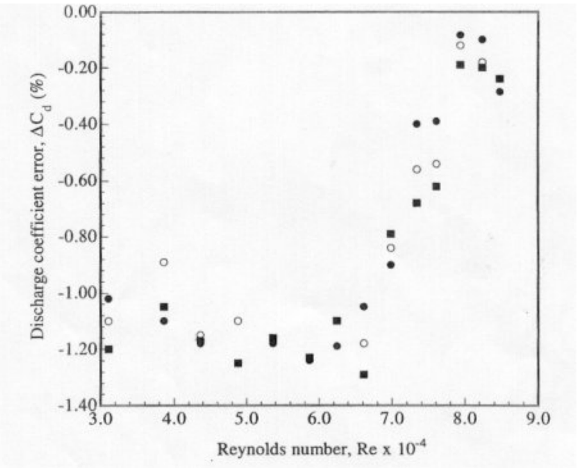

Figure 11. Discharge coefficient for NEL plate orifice meter package, $\beta = 0.7$: valve fully opened; o valve 50% closed, valve 70% closed