THE PRODUCTION OF SWIRL IN OIL AND METHOD OF COMPENSATION IN MULTI-PATH ULTRASONIC FLOWMETERS

T. Cousins, B. Griffith
Cameron, Caldon Ultrasonics
1000 McClaren Woods Drive,
Coraopolis, PA 15108,
USA
+1 724-273-9300

Abstract: The paper describes a series of tests, which were initially intended to investigate performance of a two plane multi-path meter in the presence of severe swirl. With the two plane design it was clear that detailed data could be produced showing the level of the swirl, its changes with distance along the pipe and even the changes in position of the swirl centre.

Most of the work previously on swirl had been conducted at high Reynolds numbers, and the assumptions were made that it takes the same form, possibly until the transition and laminar regions. The tests described range from a Reynolds number of 2000 to just under 1,000,000, thus the data covers the complete transition region and the higher laminar region. Some unusual results were obtained, showing a substantial increase in the production of swirl in the region between 10,000 and 100,000, tailing off as the Reynolds numbers become higher. In this region the swirl appears to be large and to a degree unstable.

The paper details the data and also shows the intrinsic ability of the two plane meter to deal with the effects of swirl, even when it is not concentric.

Keyword: Multi-Path USM, Swirl, Ultrasonic Flowmeters,

1.0 Introduction

For many years, starting with the early Westinghouse multi-path chordal meter designs, it has been suggested that multi-path ultrasonic flowmeters (USM's) are immune to swirl. Reading the small print, however, there has always been the rider that the swirl should be centered. Almost by definition swirl is unstable and very unlikely to be centered, but is more likely to be contra-rotating pairs or corkscrewing along the pipeline. As a consequence in Gas measurement, for example, most gas ultrasonic flow meters are used with flow conditioners. The eight path, two plane, meter was conceived by Westinghouse in the 1980's to resolve the problem of non-centered swirl.

Over the years most of the swirl testing for USM's has been for gases and liquids at high Reynolds numbers, with very little data on oils. In particular heavier oils are becoming a larger part of measurement requirements, depressing the Reynolds number to 100,000 and below, and even into the transition and laminar regions. There has been very little data on the swirl produced and the effect on the USM at these Reynolds numbers.

The tests described were originally designed to demonstrate the performance of the two plane, eight path meter, in installations simulating those on a pipe line at the pump stations. The results obtained were of such a nature as require further testing with other installations, looking at the effect on both four and eight path meters and how the CPA conditioner plate modified the flow into an Ultrasonic flowmeter.

2.0 Meter Description

The two meters tested were 6" diameter two plane, eight path transit time meters, using Gaussian quadrature distribution chordal spacing's for the transducer paths. The two meters had a different solution to the Gaussian equation. The Jacobian spacing used by many meter designs, mainly because the outer paths are further from the walls, allowing more room for transducers, and original Westinghouse Legendre solution used for the majority of the Cameron Caldon meters. At high Reynolds numbers the two operate in a similar manner, but lower down, below 500,000 the Jacobian spacing has a pronounce non-linearity compared to the Legendre. A description of the equations and meter operation has been given in numerous papers by Brown and others [1,3,4].

The meter used for testing is a cross path, two plane eight path meter. The cross paths are used to remove the effect of swirl on the paths. The improvement due to the two sets of paths being in orthogonal planes is the cancellation of the transverse velocity components due to swirl. The method ensures the cancellation of these components as they effect the orthogonal paths in the same magnitude, but in opposite directions, as shown in Figure 1. For this to operate, however, the planes have to be at the same measuring point. If this is not the case, and for example, the second path is further downstream in the form of a second meter, there is a high probability that the asymmetry will have changed, and the cancellation will be incorrect.

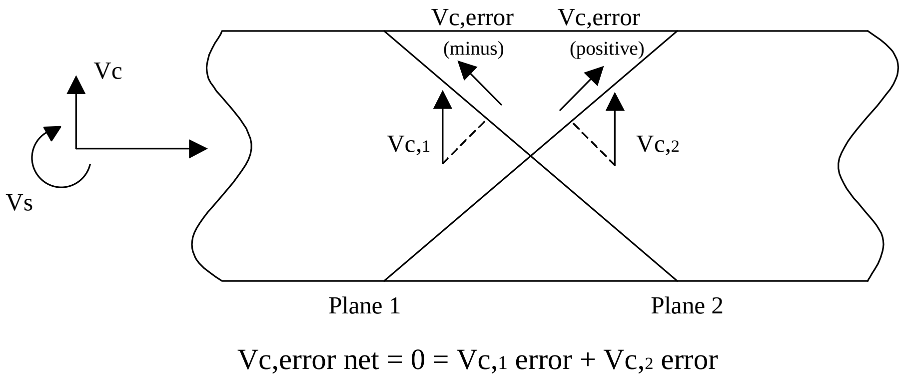


Figure 1: Method of Swirl Removal Using Two Orthogonal paths

In terms of quantifying the swirl produced, this method has a second advantage; the amount of swirl can be calculated, thus allowing collection of data relating to swirl in pipes, over a wide range of Reynolds numbers.

A further advantage of this design, particular from the perspective of the following tests, is that it could be tested as three different meters, the eight path configuration, Figure 2, two single plane, four path meters, Figure 3, and finally two four path meters with offset orthogonal paths Figure 4.

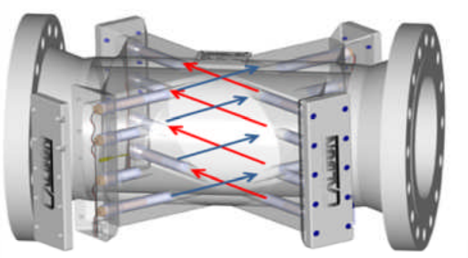


Figure 2: Two Plane Eight path Meter

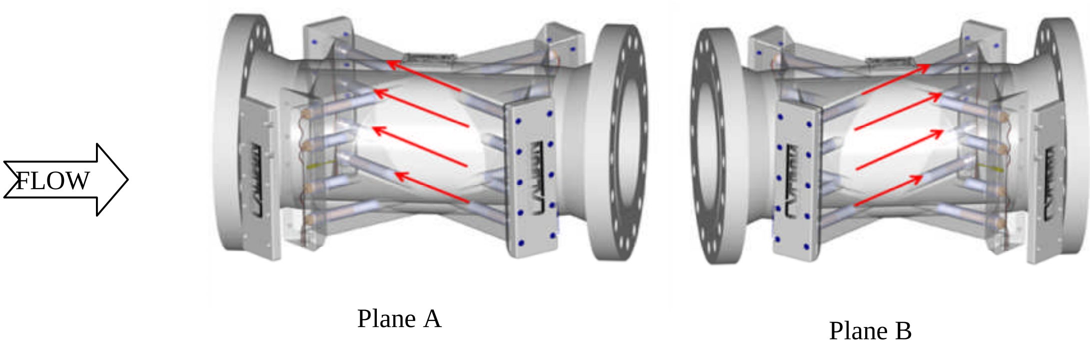


Figure 3: Four Path Meters Single plane

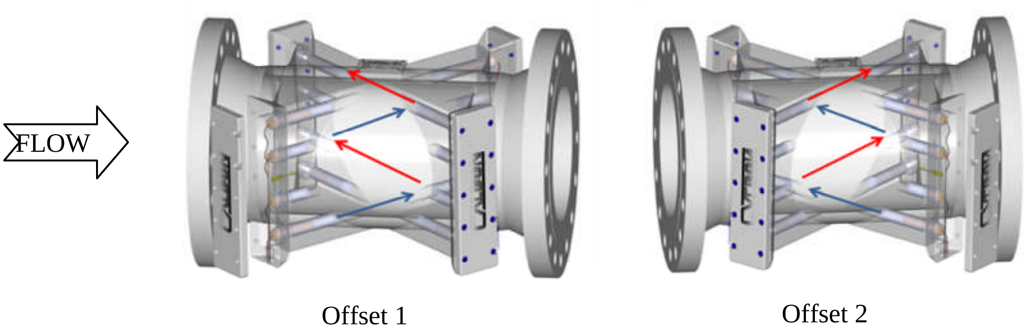


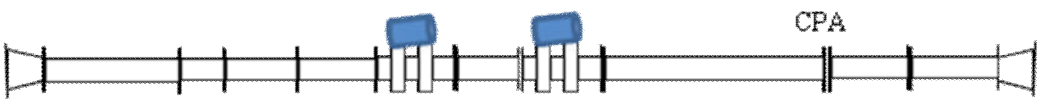
Figure 4: Four path Offset Plane

3.0 Installations and Test Facility

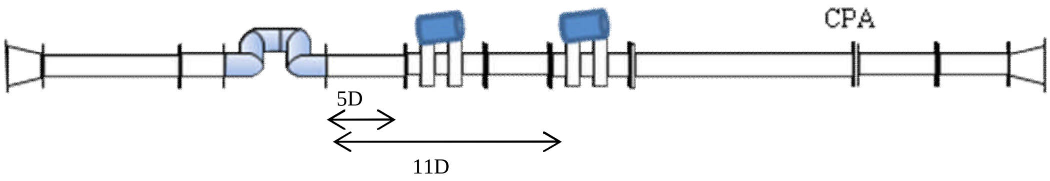
The installations tested are shown below. The initial installations were used to simulate the operational conditions, the latter installations to review how swirl and the effect on the meter performance would be modified if the 3 inlet bends were dissociated from the outlet 3 bends. Further, data was collected on the performance of the CPA plate with all meter types.

3.1 Original Installations

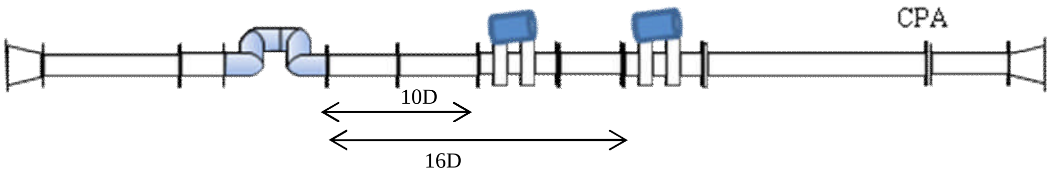
3.1.1 Straight Pipe Installation



3.1.2 Swirl Installation 1 (6 Elbow-6E)



3.1.3 Swirl Installation 2 (6 Elbow-6E)



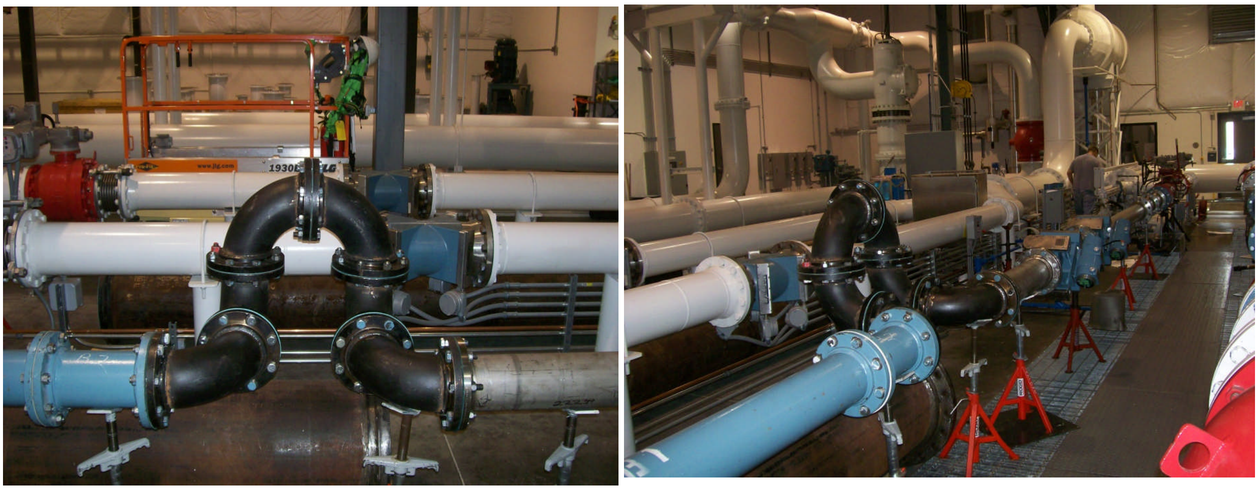


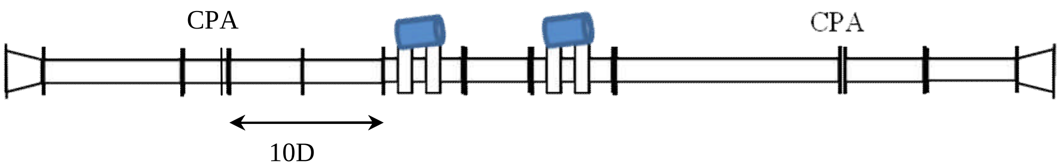
Figure 5: Photos of the Actual 6 Elbow Installation

3.2 Follow-up Installation

There are three different installations tested:

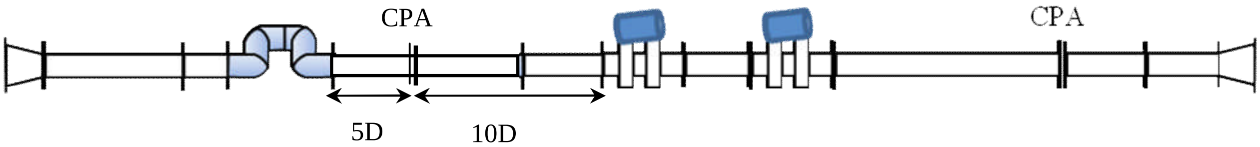
3.2.1 Straight Pipe with CPA Plate Installation

The installation for the CPA plate in a straight meter run is shown below. The first meter is 10 diameters form the CPA and second 16.



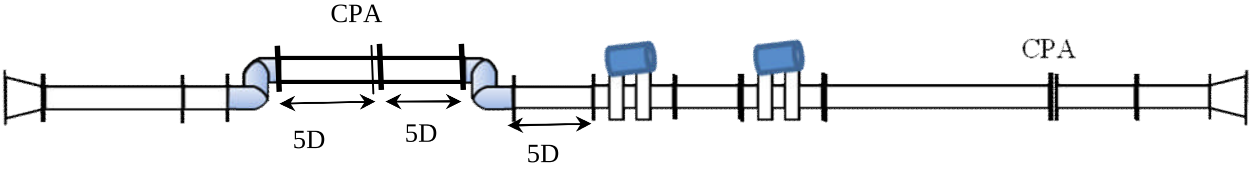
3.2.2 Original Swirl Producer + CPA Plate (6 Elbow-6E)

The original swirl producer from Section 3.1 was used and the CPA plate placed 5 pipe diameters from the end of the swirl source, and 10 pipe diameters upstream of the first meter. The second meter is subsequently 16 diameters from the CPA plate. This is called the 6E configuration (6 Elbows)



3.2.3 Installation with the Downstream Bends Dissociated from the Upstream Bends (3 Elbow-3E)

The installation that attempts to isolate the upstream and downstream bends is shown below. This is called the 3E Configuration (3 Elbows)



3.3 Test Facility

The meters were tested at the Cameron Caldon ISO 17025 accredited at Pittsburgh in the USA. The facility allows meters from 2" to 24" to be calibrated at a variety of uncertainties dependent on the calibration method. For these tests the meter were calibrated against a 10m^3 uni-directional ball prover, with an accredited uncertainty of 0.04%. Three oils, with nominal viscosities of 2, 13 and 150 cS were used to give a nominal Reynolds number range of 2000 to 700,000, a 350:1 range. The design of the facility is described in a paper by Griffith, et al. [2].

4.0 Swirl and Meter Factor Calculation Methods

Swirl Rate

The rate of swirl can be calculated from the following eaquation for an eight path, two plane meter. It treats the swirl as though it is a solid wheel of rotating fluid, and so it is a good indicator of the swirl, but is not an accurate representation of complex swirl.

$$\text{Swirl Rate} = \text{Average}\left[\frac{V_1 - V_5}{2\cdot y_S}, \frac{V_8 - V_4}{2\cdot y_S}, \frac{V_2 - V_6}{2\cdot y_L}, \frac{V_7 - V_3}{2\cdot y_L}\right]$$

Where:

V_1, V_4, V_5, V_8	=	Normalized velocities measured along outside/short chords
V_2, V_3, V_6, V_7	=	Normalized velocities measured along inside/long chords
y_S , y_L	=	Normalized chord location for outside/short and inside/long paths

This gives the swirl, or cross-flow as a proportion of the axial flow. Swirl rates computed to be less than 3% are considered to be low and are typically observed in models with only planar connections. Swirl rates greater than 3% are considered "swirling". Swirl rates greater than 10% are considered to have strong swirl.

To calculate the meter factors for all variations, the method used was to take the normalised velocities, Vnorms, and add them together with the weighting factors. This should be unity.

The mean normalized velocity for each set of paths is given by:

$$V_{npaths} = \sum_1^n VnKn$$

Where V_{npaths} is the normalized mean velocity for the number of paths in the meter, V_n is the normalized path velocity and K_n is the weighting factor for the path n.
The calibration data collected included the meter factor for the eight path meter and the individual normal velocities from each path.
To obtain the MF for the 4 path meters, the equation is given by:

$$MF_8/V_{4paths}$$

Where MF_8 is the 8 path meter factor and V_{4paths} is the calculated mean normalized velocity for the individual 4 path meters.

5.0 Swirl Produced

The swirl produced during the initial tests, using the 6 elbow configuration, is shown in Figure 6. The unusual aspect of the data is that, for the 6 elbow swirl case, the swirl increases from a low Reynolds number to a maximum at around 30,000 and then begins to decay, possibly flattening out at the highest Reynolds numbers. This was unexpected, and seemed to be showing that at the higher Reynolds numbers the swirl was being destroyed by the turbulence. However, a closer look at the installation and the meter design gives other possibilities. The increase in the region of 10,000 to 30,000 could have been a mis-reading of the velocities from the meter, possibly due to porting effects; however, as will be seen in Figure 6, this does not exhibit itself with the three bend configuration. What appears the most likely solution is that the swirl produced by the first three bends is in the opposite direction to that produced in the second three bends, and depending upon Reynolds number there is a degree of cancelling. Referring to Figure 6, it can be seen that the swirl continues to increase with increasing Reynolds number, as perhaps would be expected, there being less viscous drag to decay the swirl.

Note in both graphs the two meters show similar values and trends of swirl, particularly at the 10/11 pipe diameter position, giving a good degree of confidence in the method. It should also be noted that the swirl does decay with distance from the source, although this is reduced at higher and lower Reynolds numbers.

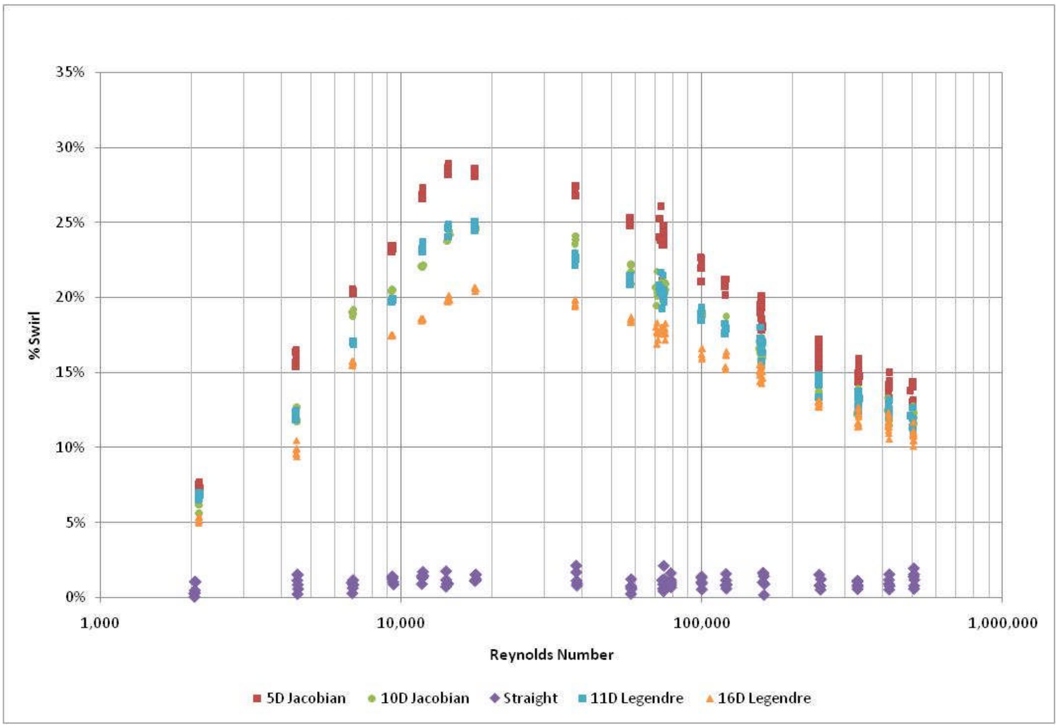


Figure 6: Swirl Produced by the 6 Elbow Configuration

As can be seen from Figure 7, the levels of swirl are higher in the 3 elbow configuration than the 6 elbow, and the amount continues to climb with increasing Reynolds number. The CPA plate does a good job of reducing the swirl in the 6 elbow configuration, but does take, with both meters the swirl marginally negative, up to 5%, in the Reynolds number range where the swirl peaked, for the 6 elbow configuration.

For both sets of swirl producing installations the swirl produced is large. The second set using the 3 elbow concept reaching as high as 38%. This would imply that the non-axial velocity is 38% of the mean axial velocity although this is treating the swirl as though it is a spinning disc and so is only an indication of the real values in the fluid.

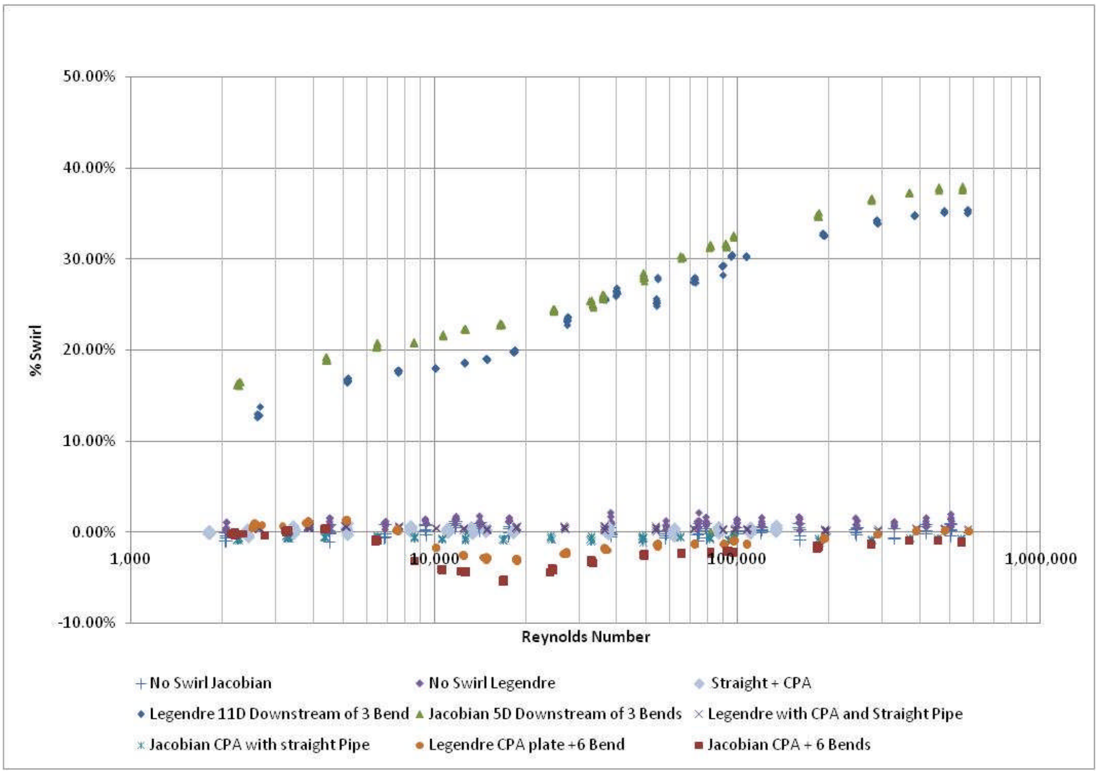


Figure 7: Swirl Produced in the Second Series of Tests

6.0 Effect on Profile

It has become traditional in USM's to rely on flatness ratio, a measure of how "peaky" the profile is to indicate the fluid conditions in the pipe. At low Reynolds numbers the flatness would indicate a fast changing peaky profile with Reynolds number, flattening out at higher Reynolds numbers. Swirl is usually indicated by a very flat, often asymmetric profile. The problem is that other installation effects have a similar profile, and so if swirl cannot be suppressed in the measurement, there is no indication of the reality of the flow. In the next series of pictures we actually show the profile as it varies with Reynolds number for each of the tests, and the effect of using the eight path cancellation. The set in figure 8, are for the Legendre meter with all installations, showing the effect on the 4 path profile and the resultant 8 path. The Jacobian meter showed similar results.

The noteworthy points are that the addition of the CPA plate in the straight pipe does not materially affect the profile, and in fact the flatness of the two is very similar. The CPA plate does a good job of improving the profile with the 6 elbow swirl producer, and in fact brings the flatness back to that of the straight pipe. The effect on the profile for the four path meters is to skew the profile in opposite directions depending on the plane. The eight path meter is able to make, in all conditions tested a more symmetrical profile, although it is flatter than that for a straight pipe. The Jacobian meter had a similar effect.

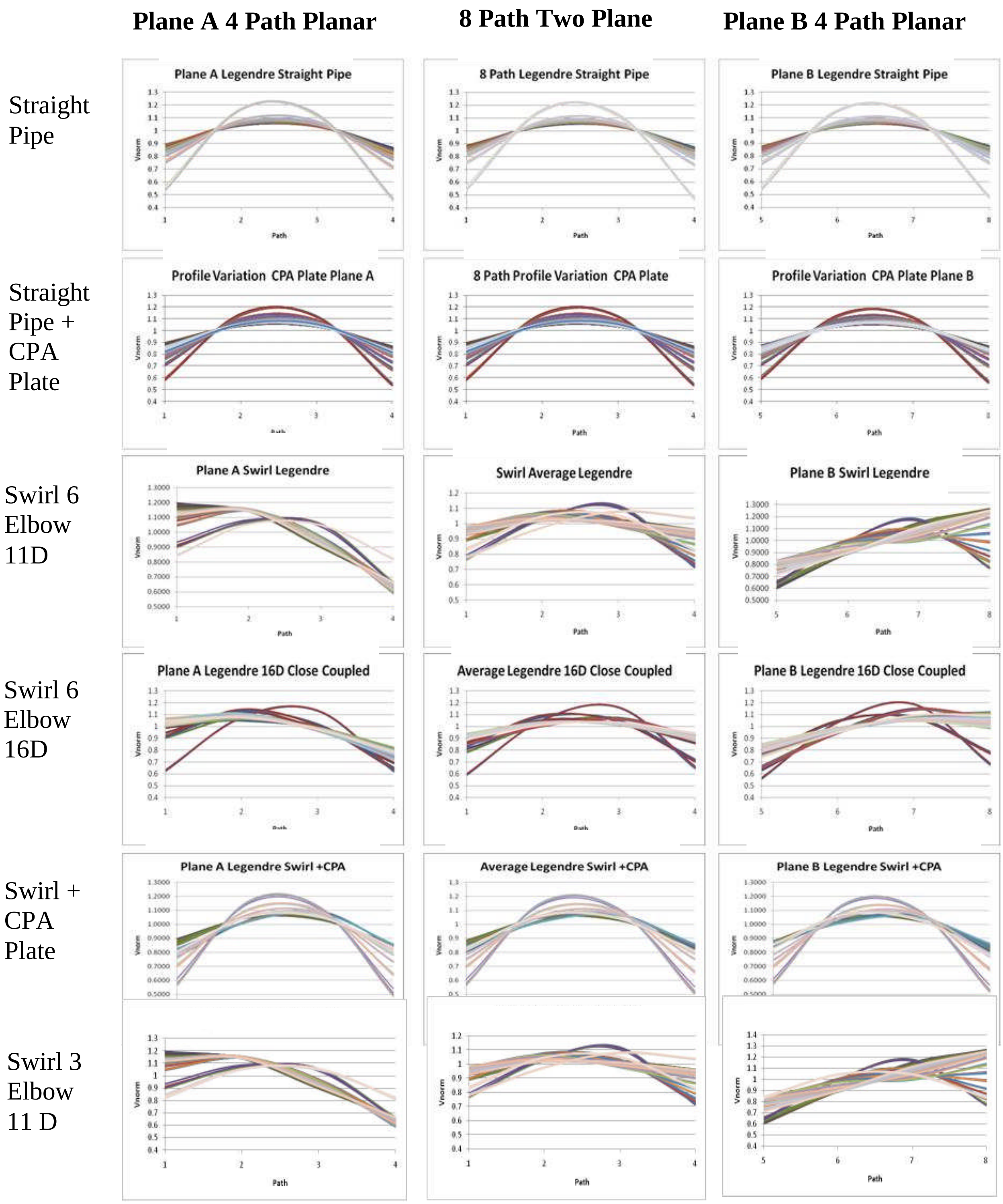


Figure 8: Profiles for the Legendre Meter Tests

The meter using offset planes for the four paths, shows a different picture. Figure 9 shows the profiles for the two path configurations on the Jacobian meter. With the paths offset in one direction the profile is symmetrical and inverted, in the other it symmetrical but has a profile similar to a marginally flat standard profile. This indicates that it is possible with the offset configuration to miss the effect of swirl in the diagnostics.

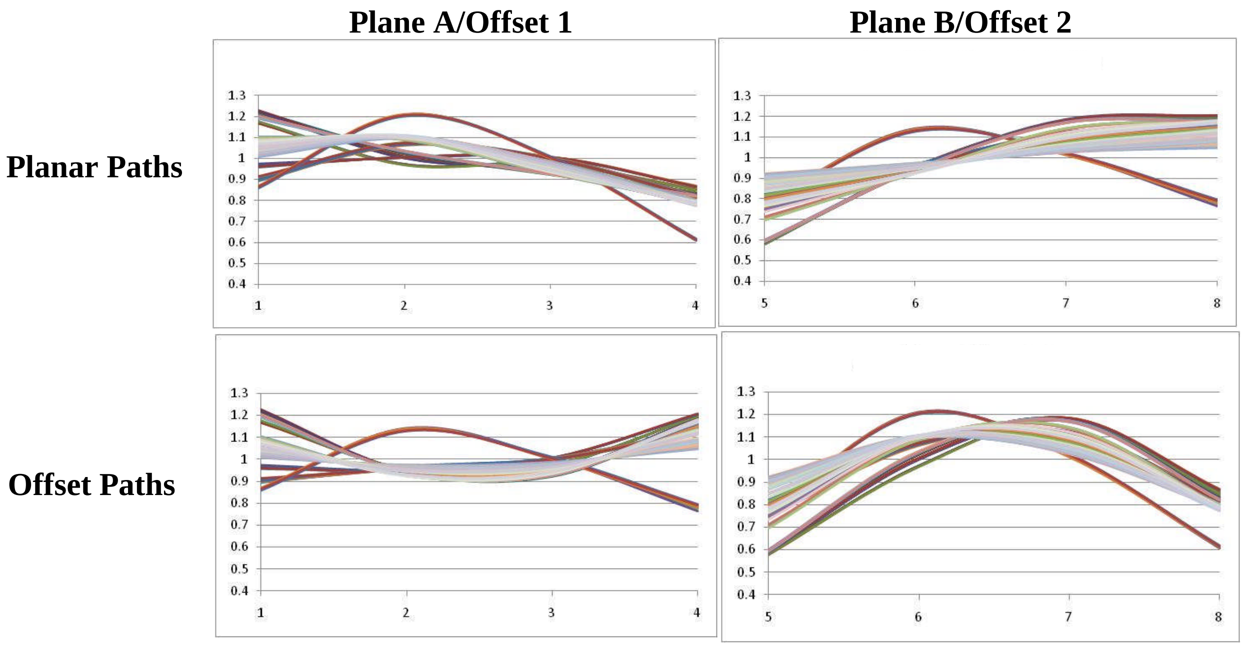


Figure 9: Profiles for the Jacobian Meter 5 Pipe Diameters from the 3 Elbow Configuration

7.0 Effect on Calibration

The effect on the calibration on the different installations varies with the type of path configuration. As can be seen from the following calibration curves the eight path configuration is considerably more resilient to the installations tested than either of the four path methods. Figure 10 shows the calibration of the Legendre eight path meter under all installation conditions tested. It is uncharacterized. As can be seen the average deviations are below +/- 0.25% for all installations. The worst case is around the 10,000 to 30,000 Reynolds number range. As the Reynolds number increases the differences become less, nearer +/- 0.05%, which is close to the uncertainty of the calibration. Considering the level of swirl encountered in these tests this shows this meter to be very resilient to installation effects.

The four path configurations have calibrations that are mirror images for each plane or offset, centered about the eight path, as would be expected. Over the Reynolds number range they are not, however, a constantly spaced mirror image, they vary considerably depending on the installation. Particularly in the Reynolds number range 10,000 to 50,000, the four path meters exhibit some sharp changes in calibration curve. Only the data for the Legendre meter is shown in this paper for conciseness. The Jacobian meter, which has a similar data set, will be shown in a later paper.

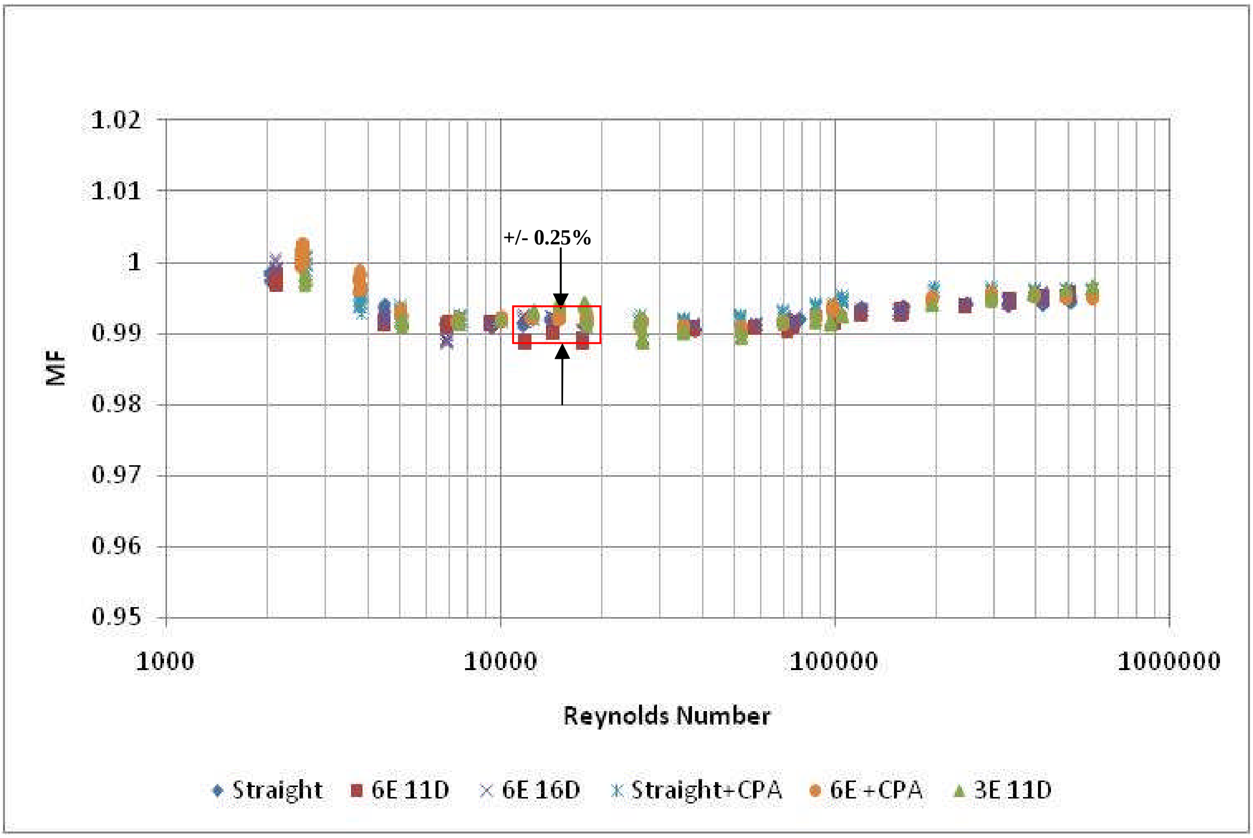


Figure 10: Calibration of the Legendre Eight Path Meter with all Configurations

The calibrations of the four path configurations are far more effected than for the eight path by installation variations. As stated previously the opposite planes have mirror images of the calibrations, as shown, for example, in Figures 11 and 12, the swirl cases for the planar meters and the offset meters. This data is repeated for all installations, including the starighit pipe. The consequences of the mirror imaging, do allow the possibility for a numerical check of the eight path meter performance, a concept that has been used for a number of years on the meters used for feedwater measurement in the Nuclear industry.

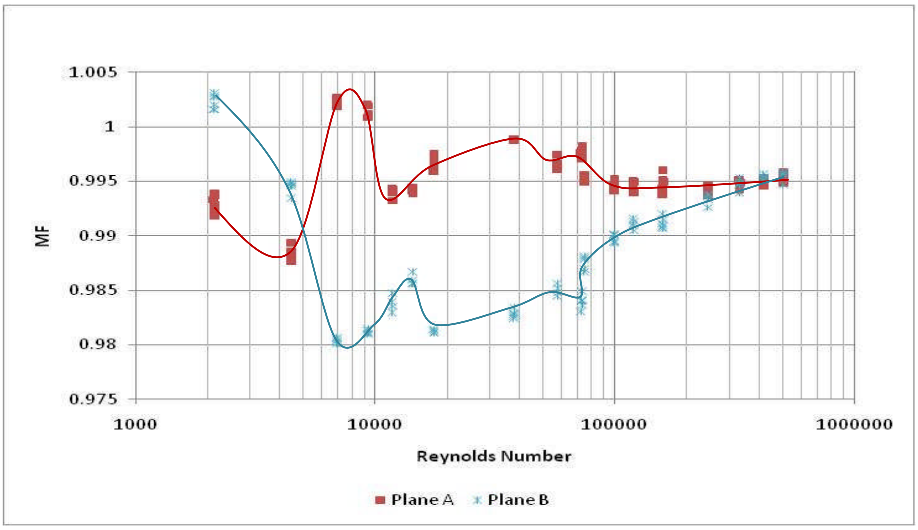


Figure 11: Calibration of Legendre Single Plane Meter with 6 Elbows at 11 Diameters

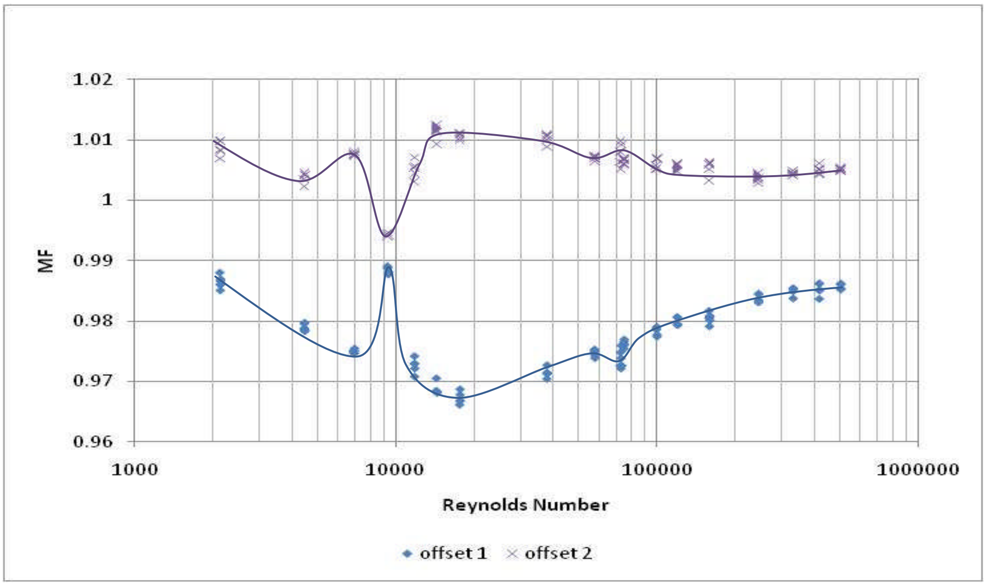


Figure 12: Calibration of Legendre Offset Meter with 6 Elbows at 11 Diameters

Both curves show how even the smallest variations are mirrored in the two planes. The single plane meter even has a cross-over of calibrations at low Reynolds number, but retains the mirror image.

The effect of all the installations on the four path meters are shown in Figures 13 and 14. Only one plane, or offset is shown to reduce the amount of data on the graphs. In both cases the other plane, or offset, is a mirror image of the changes in the graphs shown.

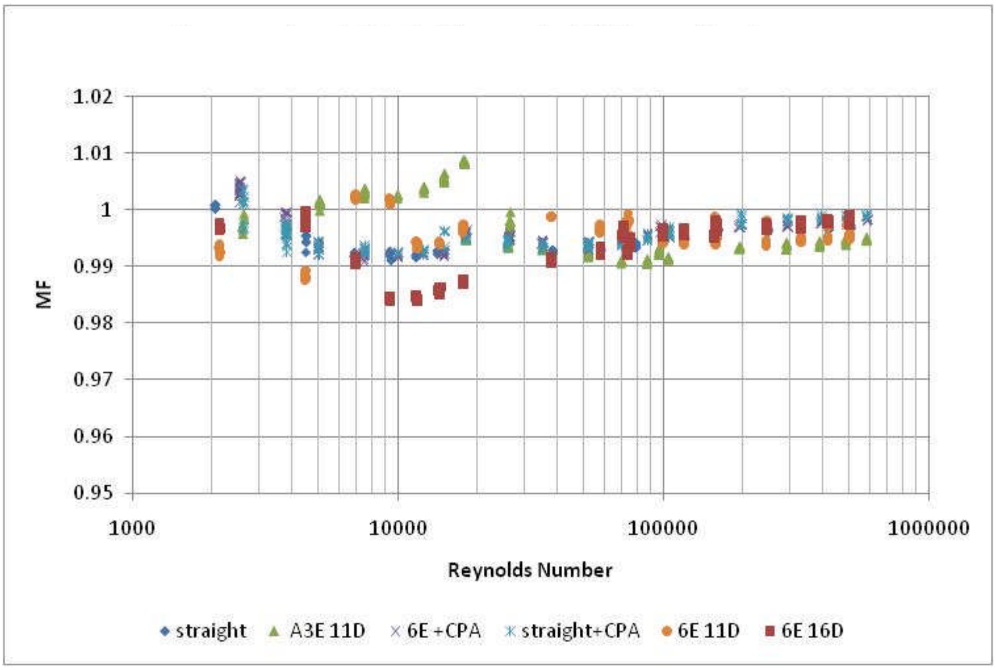


Figure 13: Calibration of Legendre Single Plane Four Path Meter with All Installations

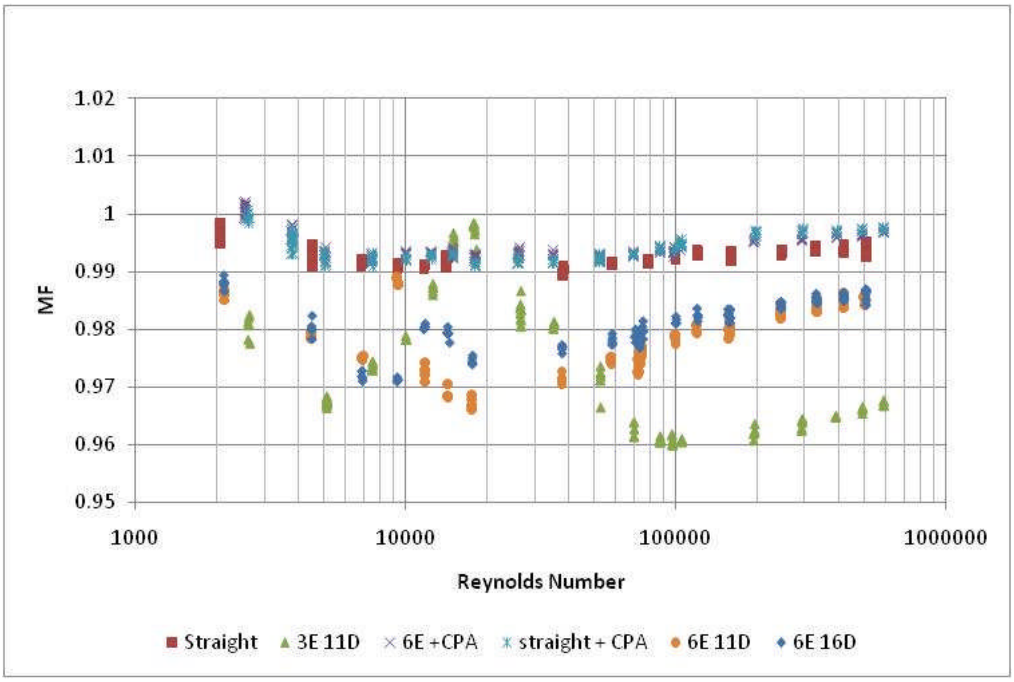


Figure 14: Calibration of Legendre Offset Four Path Meter with All Installations

In both cases the deviations of the calibrations due to swirl is significant, in the single plane case the variations are from +/- 0.4% at high Reynolds numbers to +/- 1.0% in the range 0f 10,000 to 50,000. The offset meter for the same installations is nearer +/- 1.5% in spread, with no improvement as the Reynolds number increases.

The CPA plate, however, appears very effective at reducing the effect of swirl on both the single plane and offset plane meter. In the case of the single plane it has brought the errors down close to the calibration uncertainty, comparing the calibrations for swirl with the plate (6E + CPA), the straight with a CPA and a straight pipe. There is a small change for the offset meter. This may in fact be an effect of the CPA plate, because the CPA plate with straight pipe shows a similar change from the straight pipe condition at high Reynolds numbers. It does show, however, that calibrating the meter with the plate will be effective in negating the effects of these installation conditions.

8.0 Conclusions

8.1 There is a significant difference in the swirl generated by the 6 Elbow bend configuration and the nominal 3 Elbow.

8.1.1 The 6 Elbow configuration appears to have some form of cancelling at higher Reynolds numbers, presumably due to the opposite swirl generated by the two sections.

8.1.2 The 3 Elbow configuration shows an increasing swirl as Reynolds number increases.

8.1.3 There is an effect on the meters in the Reynolds number range 10,000 to 30,000 that causes some instability particularly in the four path meters.

8.1.4 It is clear that it is very difficult to guess the swirl/flow patterns just from a visual inspection of the installation.

8.2 The eight path, two plane, configuration for both path configurations does show very little change in calibration even with severe swirl.

8.3 The comparison of the two four paths meters does offer a chance to see profile distortions, and to a small degree quantify them. They are remarkably symmetrical for both path configurations.

8.4 The four path configurations are very prone to changes in calibration, particularly with the presence of swirl.

8.4.1 This meter for custody transfer should always be used with a flow conditioner.

8.4.2 The CPA plate tested did a good job of correcting for the installation conditions.

8.4.3 The planar four path meter, for the installations tested, is better than the offset four path arrangement.

8.4.4 Offset configuration also gives two contrary profiles in the presence of swirl, one of which looks like a symmetrical fully developed profile.

8.5 The CPA plate tested, at 10 and 15 diameters from the two meters did not materially affect the calibration compared to straight pipe installation.

8.5.1 It did a good job of getting rid of the swirl and making the profile more symmetrical

8.5.2 It worked well at protecting the four path configuration meters.

8.6 Above 100,000 Reynolds numbers the Legendre path spacing appears to be very stable, even with very strong swirl.

9.0 References

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