THE PERFORMANCE OF A MODIFIED ELECTROMAGNETIC FLOWMETER WHEN ABUTTED TO A SMALLER MISALIGNED UPSTREAM DIAMETER PIPE

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Abstract: Electromagnetic flowmeters are today widely used for industrial flow measurement. For industrial users, due to physical constraints, the installation recommendations contained in national and international standards may not be achievable. The actual installation then results in the flowmeter being exposed to velocity profiles which are not fully developed, and do not accord with the situation for which the meter was designed and calibrated. The influence of a smaller upstream diameter pipe together with pipeline misalignment, when abutted to an electromagnetic flowmeter, is discussed.

Keywords: Electromagnetic Flowmeters, Laser Doppler Anemometry, Misalignment Effects

1 INTRODUCTION

The standard BS 5792 / ISO 6817 [1], defines the electromagnetic flowmeter as an assembly which comprises of a primary metering device, through which the fluid to be measured flows, together with a secondary device which converts the low level signal, generated by the primary device, into a suitable signal for acceptance by industrial instrumentation. The system produces an output signal proportional to the average volumetric flow rate. Its application is generally limited only by the requirement that the metered fluid shall be conductive and non-magnetic. The principle of operation is based on Faraday's Law of Magnetic Induction. When a conductive liquid passes through a magnetic field, a voltage is generated at right angles to the velocity and magnetic-field vectors. That is, the voltage that is generated by the flowmeter, is mutually perpendicular to the flow direction and the magnetic field, and is detected by diametrically opposed electrodes across the diameter of a non-conducting pipe wall. The signal voltage is a summation of individual voltages generated by differential volumes moving at differing velocities across the pipe section. Based on the principle of magnetic induction, the magnetic flowmeter provides a noninvasive method that essentially averages the fluid's velocity over the pipe's cross sectional area. The relationship being represented by[2] :

$$V_S = CdB\bar{u} \qquad (1)$$

where, $\mathbf{V_S}$ is the signal voltage measured in volts, **d** is the distance between the electrodes expressed in metres, **B** is the magnetic flux density in tesla, $\bar{u}$ is the average velocity in m/s and **C** is a calibration constant determined by the manufacturer. With properly selected liners for the pipe wall, magnetic flowmeters are ideally suited for slurries, dirty flows, pulp stock, non-Newtonian fluids and corrosive liquids. The main advantage with these flowmeters for industrial users is their linearity as shown by equation (1) over a range of accuracy envelope such that a ± 2 % or less error signal is typical at very low flow rates and up to ± 0.125 % for high flow-rates. It must be stressed however that the design is based on the assumption that idealised velocity profiles are always encountered, this means that fully developed parabolic or power law mean velocity relationships exist for laminar or turbulent flows respectively.

Industrial use of these flowmeters is to-day widespread, unfortunately their installed location seldom accommodates fully the recommended conditions outlined in international standards or the manufacturers design/calibration assumptions. BS 7526/ISO 9104[3] specifies that the primary device should be installed in a straight pipe, at a distance of at least ten diameters from any upstream disturbance and five diameters from any downstream disturbance. It is therefore not surprising that the manufacturers undertake research programmes, in support of their products, in order to establish how the overall performance of their flowmeters is affected by upstream flow conditions.

Manufacturers investigate the performance of their products under not only the idealised flow conditions, as required by national and international flow standards, but also in circumstances where disturbed velocity profiles have been deliberately generated. Modern experimental techniques such as **l**aser **D**oppler **a**nemometry(**LDA**) and **p**article **i**mage **v**elocimetry(**PIV**) enable detailed nonintrusive measurements of both the mean velocity and turbulence structure. Detailed **LDA** measurements of the axial velocity in two planes at 90° to each other(horizontal and vertical)have been reported within a modified 50 mm diameter Danfoss flowmeter[4] and immediately upstream from two nominally 152.4 mm diameter flowmeters, for different upstream pipeline configurations[5],[6],[7]. The pipeline configurations considered in these studies were typically the same as those experienced in industry, in which flow disturbances are encountered, that is - distorted mean velocity profiles, very high turbulence levels and time instabilities. These flow disturbances may be associated with a degree of misalignment, single, double and triple bends in various planes and a combination of bends, which immediately abut to a flow reducer. The performance of a modified Danfoss DN50 (nominally of 50 mm diameter bore) electromagnetic flowmeter has been reported in the literature [4] when installed downstream from three different diameter pipes, these pipes, each of 3 m length, had nominal diameters of 50 mm, 55 mm and 45 mm respectively.

BS 7526/ISO 9104[3] indicates that the internal diameter of the pipe, which is connected to the flowmeter, should be the same diameter or not more than 3% greater than the internal diameter of the flowmeter. This current presentation therefore provides details on the performance of the flowmeter when this installation recommendation was significantly contravened.
Three configurations were considered for the 45 mm diameter upstream pipe, namely:

1. the centre line of the electromagnetic flowmeter was inline with that of the upstream pipeline. For the 45-mm/DN50-inline configuration a symmetrical abrupt expansion is encountered by the flow, the nominal height of the square edged backward facing step being 2.5 mm, all around the circumference. This will give a submerged jet flow at the entrance to the flowmeter. The flow as it issues from the smaller inlet pipe will have an associated recirculation region immediately downstream from the abrupt expansion. The size and strength of the recirculation region will be influenced by the nature of the internal surfaces immediately around the contraction.
2. the centre line of the flowmeter was misaligned in the horizontal plane by 3 mm, the flowmeter's electrodes being in the horizontal plane. This 3 mm misalignment of the meter creates a square edged backward facing step on one side of the horizontal diameter with a nominal step height of 5.5 mm. On the opposite side of the horizontal diameter a forward facing rounded step is present with a nominal height of 0.5 mm.
3. the centre line of the flowmeter was misaligned in the vertical plane by 3 mm, the electrodes remaining in the horizontal plane. This 3 mm vertical misalignment represents the internal geometry outlined in the previous case with a 90° rotation.

The results provide details of the mean and rms axial velocity profiles 70 mm upstream from the electrodes of the modified electromagnetic flowmeter and highlights how the wall mean velocity gradients vary for each of the three configurations. The presence of time dependent instabilities is also demonstrated.

2 MODIFIED DANFOSS DN50 FLOWMETER/EXPERIMENTAL FACILITY[4]

In comparison with the standard Danfoss DN50 flowmeter, from the MAGFLO range of instruments, the length of the modified unit was extended symmetrically, between the flanges at either end and the electromagnetic housing, by 30 mm on either side of the centre line. This extension enabled four crown glass optical windows to be installed at either end; these access apertures were designed to give a viewing window 30 mm long by 4 mm wide. These windows were installed to give optical access, in both the vertical and horizontal planes. The DN50 flowmeter was rubber lined with a

nominal diameter of 50 mm. The inlet curvature of the flowmeter, between the flange and bore at either end, was 7.5 mm; this feature being designed by the manufacturer so as to accommodate some degree of misalignment. A two reservoir water flow facility provided a constant head via an upper reservoir, from the upper level the water flowed into the 3 m length of constant 45 mm diameter stainless steel pipe, which abutted to the modified flowmeter. The modified DN50 electromagnetic flowmeter was followed by a 10 diameter length of 50 mm diameter pipe, thereafter the return pipework comprised two 90^0 bends and a return line to the lower reservoir. The return line consisted of 50 mm diameter plastic pipe which incorporated two standard Danfoss DN50 electromagnetic flowmeters which the Company calibrated, by weighing, as a transfer standard unit. The upstream pipe prior to this unit was 28.6 diameters in length. The two transfer standard meters were 4 diameters apart. Just prior to the lower return reservoir the flowrate was carefully controlled via a lockable butterfly valve, together with a dual bypass system. Each bypass consisted of two identical valves, one to use as the on/off controller and the second to be set at a fixed position for the duration of the measurement programme. This combination of valves enabled the flowrate to be varied to provide a Reynolds number range, based upon the nominal 50 mm diameter and the measured average flow velocity, from 78923.5(100%) down to 4442.97(5.63%), the percentage of the maximum flowrate is shown in the adjacent brackets.
Details of the data logging arrangements for the three electromagnetic flowmeters and the LDA system employed have already been detailed in the literature [4]. In order to record statistically reliable data at each LDA measurement position 15000 validated Doppler bursts were collected. This sample size shows that the mean velocity at each location may be measured, using a 99% confidence limit with an error of 1% or less providing the turbulence intensity is less than 0.4. Additionally the corresponding error in the turbulence intensity is around 1.7%

3 EXPERIMENTAL RESULTS

3.1 Electromagnetic flowmeter

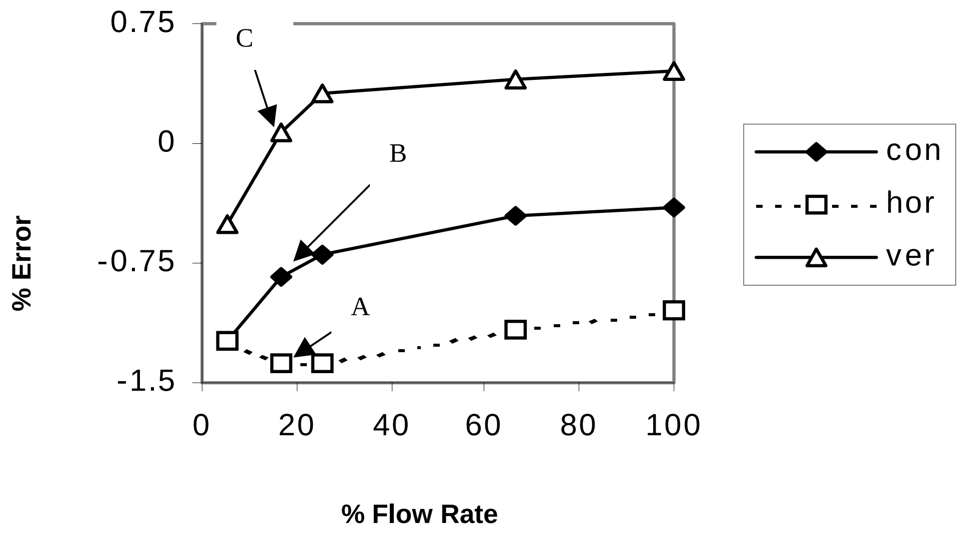


Figure 1 Percentage error variation with percentage flowrate and flowmeter alignment

The percentage error variations with percentage flowrate, for each of the three upstream pipe configurations are shown in Figure 1. Each profile shows that the error decreases at the higher flow rates. The profiles for both the concentric and vertically misaligned geometries display the same overall features with an almost constant vertical displacement between them. The concentric configuration shows that the percentage error increases with decreasing flowrate, with a maximum error of -1.2%. The negative sign shows that the modified flowmeter underpredicted the flowrate in comparison with the transfer standard unit. For the vertical misalignment the smallest overall errors are evident, the error changes sign and varies from +0.5% down to –0.5%, with a steep decline at the lower flowrates. The poorest performance is reported, not surprisingly, with the 3 mm misalignment in the horizontal plane, that is the plane of the electrodes. The maximum error around –1.4% is actually recorded for the experimental measurements around the 20% flowrate position, at the maximum flowrate the error is around –1%.

3.2 LDA Profile

(a) Horizontal misalignment

Figure 2 shows the mean and associated rms velocity profiles in the horizontal plane for the 16.9% flowrate(Reynolds number 13377), with the 3 mm misalignment in the horizontal plane, which corresponds to point **A**, on Figure 1. The mean velocity profile is not symmetric, the wall gradients, at either end of the diameter, are clearly different in comparison with a fully developed profile. A much steeper velocity gradient is evident adjacent to the wall at 0 mm, this being downstream from the small rounded forward facing step. The shallower velocity gradient is evident in the wall region at 49 mm, which is downstream from the 5.5 mm square edged backward facing step. For comparison a power law with n = 3.617 is shown, this n value corresponds to a power law which has the same ratio of the mean velocity to the maximum velocity as the experimental data. The symmetrical power law profile clearly shows the skewness evident in the measured mean velocity profile, the latter being greater than the power law from 4mm up to the centreline and much less from 37 mm to the wall(49 mm). The rms profile shows, as expected, low values over the central core and peaks adjacent to the walls. The wider peak is observed downstream from the 5.5 mm backward facing step.

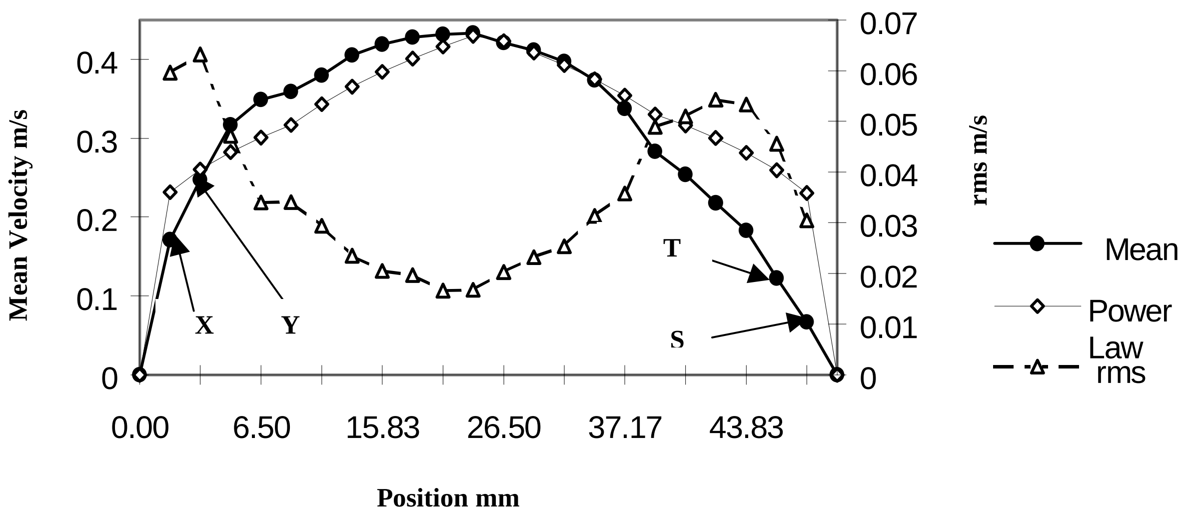


Figure 2 Mean and rms velocity profiles, horizontal misalignment, Reynolds number 13377

The centreline percentage turbulence intensity, based upon the mean flow velocity(0.305 m/s), is around 6% whilst the peak near the wall is around 20%. These values are typical of those normally observed for fully developed power laws.

Inspection of the measured LDA histograms provides evidence of regions in the flow where time dependent instabilities may be present, in addition near Gaussian distributions may be observed over the central core region of the flow. Two histograms are shown in Figure 3, the location of these two measurement positions (**X** and **Y**) are shown on Figure 2. At location **X** two distinct flow states existed, during the time interval over which the data was collected. For the dominant larger peak a mean velocity closer to 0.19 m/s is evident, which compares with an actual value for the whole sample of 0.17 m/s. At position **Y** a bimodal distribution is still evident, confirming that the velocity fluctuates between two states during the short sampling window.

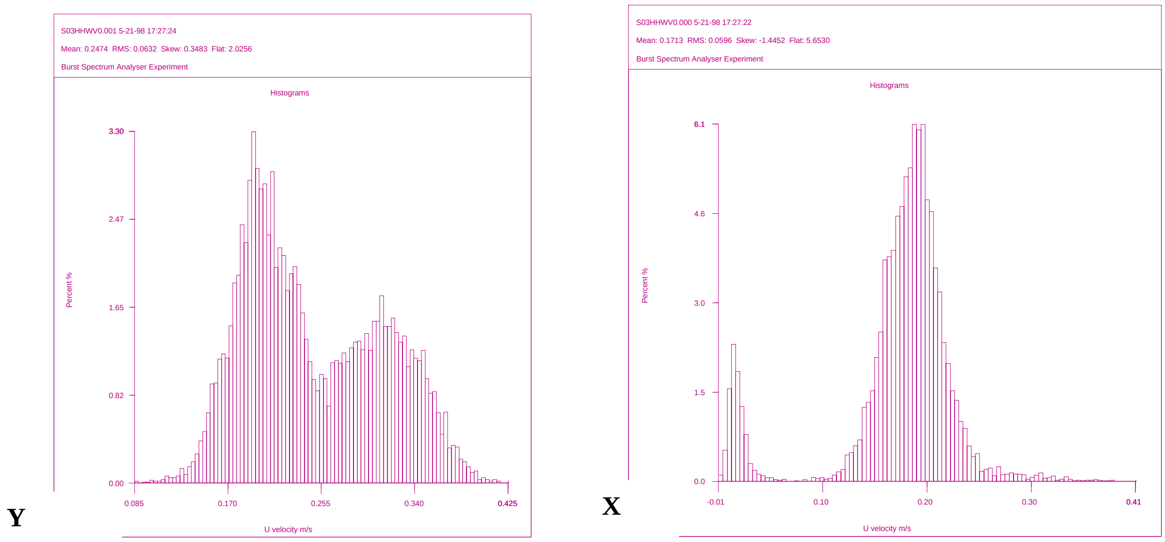


Figure 3 Measured histograms at points **X** and **Y** identified on Figure 2

(b) Vertical misalignment

Figure 4 shows the mean and rms velocity profiles measured in the horizontal plane with the flowmeter misaligned by 3 mm (upwards) in the vertical plane, these results correspond to point **C** on Figure 1. The measured mean velocity profile exhibits good symmetry, the gradients adjacent to both walls correlate well with each other. Figure 4 also includes the same power law (n=3.617), the measured and power law mean velocity profiles correlate very well with one another. The measured profile is slightly *fuller* over the whole profile apart from adjacent to the walls.

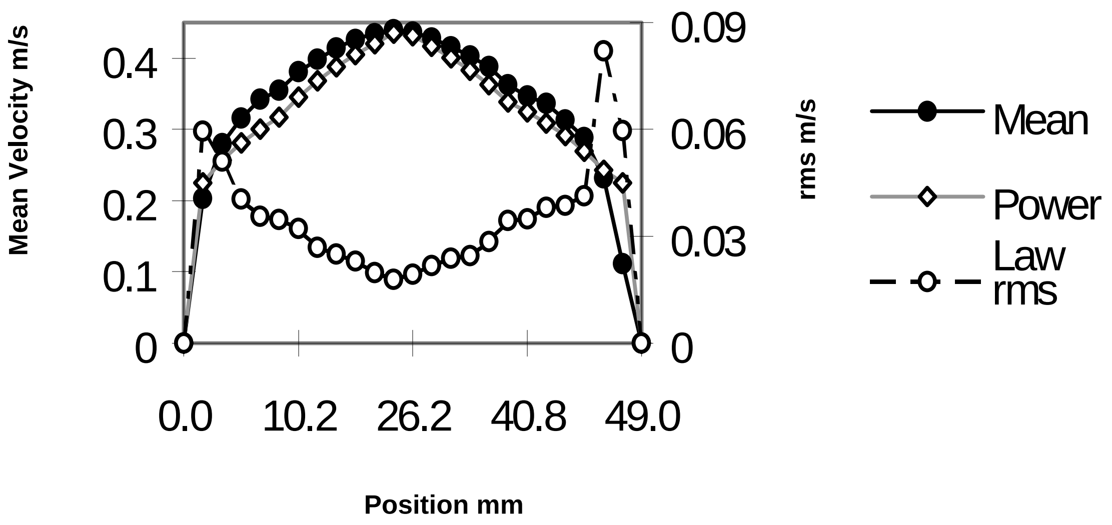


Figure 4 Mean and rms velocity profiles, vertical misalignment, Reynolds number 13377

The rms profile also shows good symmetry with a centreline percentage turbulence intensity of just under 6%. The highest rms values are evident adjacent to the window at 49 mm, with a peak turbulence intensity of 27%.

(c) Concentric alignment
Figure 5 shows the mean and rms velocity profiles in the horizontal plane, these results correspond to point **B** on Figure 1. Reasonable symmetry is evident over the central core of the mean velocity profile, however discontinuities in the profile are evident when the wall gradients are compared. The incorporated power law (n=3.617) again shows reasonable correlation with the measured profile over the central core, however variations are evident particularly in the wall regions.

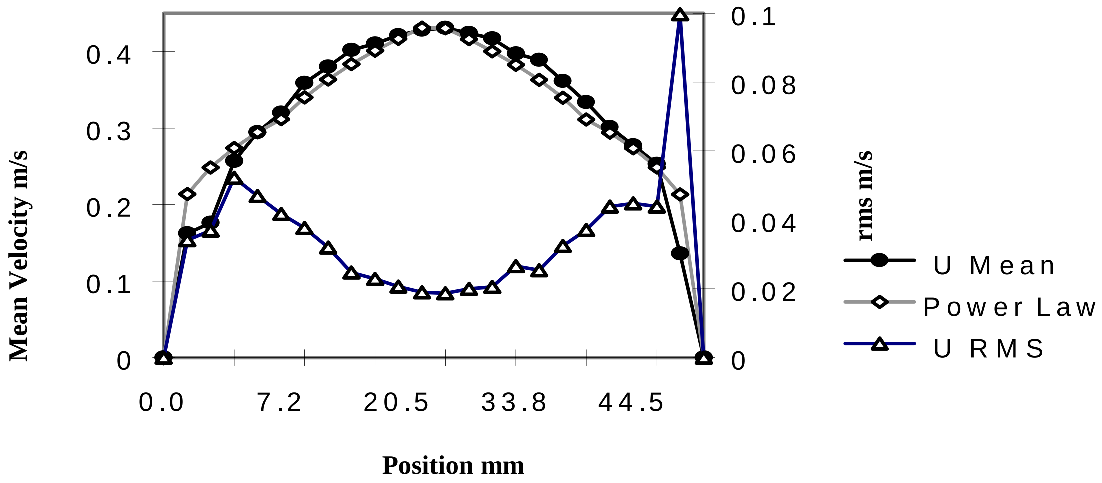


Figure 5 Mean and rms velocity profiles, concentric alignment, Reynolds number 13377

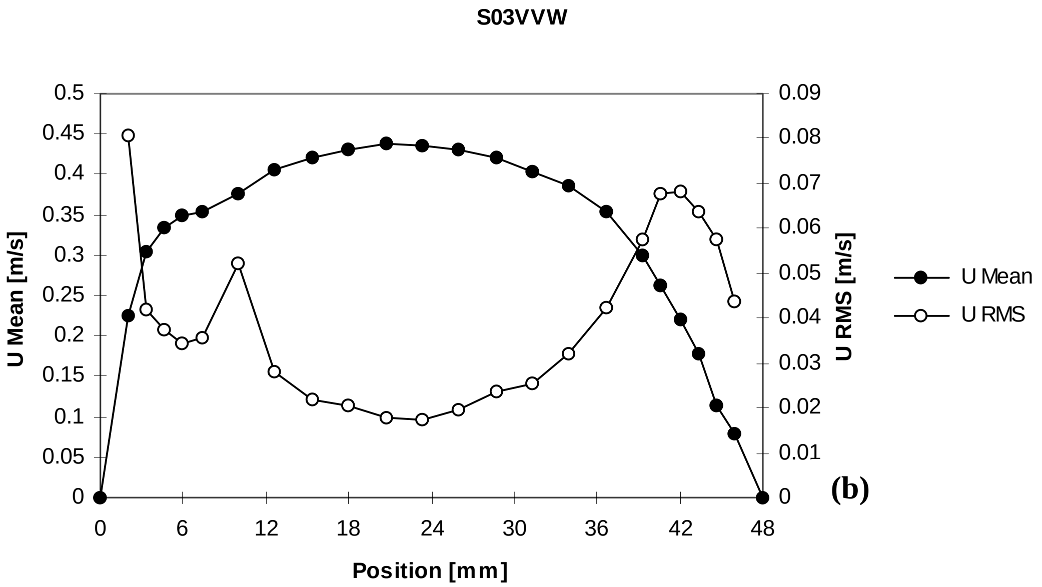
The rms velocity profile exibits good symmetry over the bulk of the flow with a minimum percentage turbulence intensity of just over 6%. A peak rms value (0.0997 m/s) is evident adjacent to the wall at 49 mm., this corresponds to a percentage turbulence intensity of 33%.

4 DISCUSSION

A power law, based upon the actual flow conditions, has been written as $U_y = U_{max}(1-y/R)^{1/3.617}$, where y is the distance from the centreline of the electromagnetic flowmeter, this power law has been incorporated into Figures 2, 4, 5 for comparison with the experimental measurements.
The main feature of the 3 mm misaligned geometries which would be expected to dominate the flow, is the presence of the 5.5 mm high square edged backward facing step. This feature existed, in different planes, for two of the geometries studied. Generally experiments on backward facing steps show that this feature is accompanied by a reverse flow region, which would be expected in this instance to cover a region of 27.5-33 mm before wall reattachment would occur. Some associated time dependent flow intermittency may be experienced. Figure 2, for the 3mm misaligment in the horizontal plane, shows that the wall gradients are significantly different at either end of the diameter and the velocity profile is skewed in comparison with the power law. The shallower gradient is downstream from the 5.5 mm backward facing step, no evidence is available confirming the existence or extent of an associated recirculation zone. With the 3 mm misalignment in the vertical plane Figure 4 shows that good mean velocity symmetry is evident and the profile correlates well in every respect with the power law. Since the LDA measurements were taken across two diameters then it is not unreasonable to expect the measurements in the vertical plane to show:

(a) for the 3 mm misalignment in the horizontal plane good symmetry of the vertical mean velocity profile.
(b) For the 3 mm misalignment in the vertical plane poor mean velocity profile symmetry and different wall gradients.

These vertical profiles are presented in Figures 6(a) and (b) respectively, as anticipated the profiles shown in Figures 2 and 4 are virtually interchanged. The features anticipated for these two figures are evident; in particular quite different slopes are evident in Figure 6(b), adjacent to the walls with poor symmetry about the centreline. Figure 6(b) also displays a broad high rms region downstream from the 5.5 mm backward facing step. The core and wall rms levels correspond well with the values shown in Figures 2 and 4 respectively.



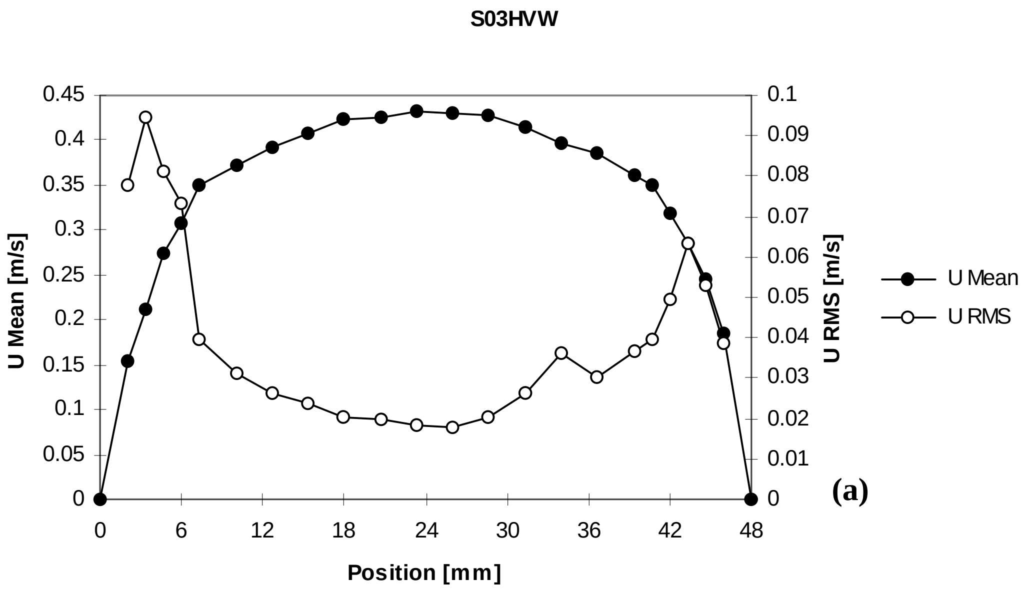


Figure 6 Vertical mean and rms velocity profiles. Reynolds number 13377
(a) 3 mm misalignment – horizontal plane
(b) 3 mm misalignment – vertical plane

For the three geometrical configurations tested the poorest performance of the electromagnetic flowmeter was achieved when the flow disturbance was in the same plane as the electrodes. From the above discussion on the wall gradients this poor performance is to be anticipated, since the electromagnetic meter is designed to work with classical velocity profiles. The manufacturer's weighting function anticipates that flow symmetry is achieved and relies heavily on the wall gradients immediately adjacent to the electrodes.
The histograms presented in Figure 3 confirm that time dependent instabilities were present.
Other features which may be associated with this would be vortex shedding, this characteristic would appear in the energy spectrum profiles such as that shown in Figure 7, for two wall positions(**S** and **T**) identified in Figure 2. Figure 7 shows clear evidence of the existence of distinct frequencies being present at these wall locations. Both profiles show the expected Kolmogoroff –5/3 slope corresponding to the decay in the inertial range, the profiles also confirm that $u'^2_T > u'^2_S$, thereby reflecting the measurements in Figure 2.

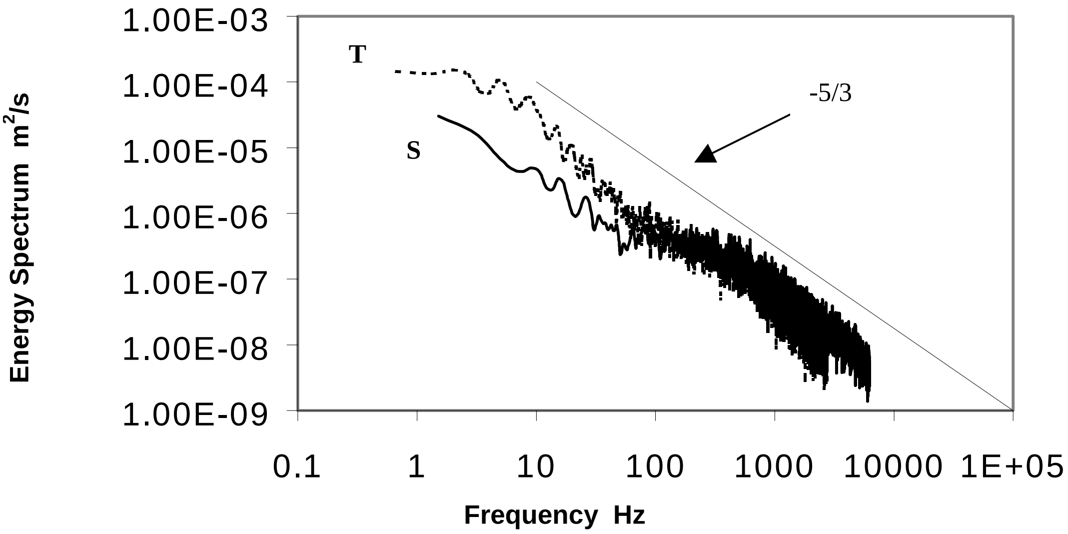


Figure 7 Energy spectrum at two wall locations **S** and **T** identified in Figure 2, Reynolds number 13377.

Conclusions

The results show that the slope of the mean velocity profile adjacent to the electrodes has the most influence on the performance of the modified electromagnetic flowmeter. This error may be reduced by installing the meter with the electrodes in a different plane. The performance of the modified electromagnetic flowmeter shows a *maximum* percentage error of around –1.4%, even though the current flow disturbances were *significantly* greater than those considered in national and international standards. This value corresponds to the configuration with the 3 mm misalignment in the horizontal plane, this being the plane of the electrodes. For this configuration the measurements also show the presence of some time dependency (intermittency) especially in the important wall regions adjacent to the electrodes.

For both the concentric and vertically misaligned geometries the measured velocity profiles exhibit much better correlation with an assumed power law, the latter being based on measured parameters. This good correlation is accompanied, in general, by much smaller flowrate errors.

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