USMs and Heavy Oil applications -The Woes of Transition and laminar Flow Measurement

by
T. Cousins OGS

Abstract

Heavy oil has three issues that can create measurement problems for liquid USMs.

A. High viscosity causes low Reynolds number flows in the transition and laminar flow regimes.
B. Temperature gradients, and therefore viscosity gradients, are common in laminar flows.
C. High viscosity causes enhanced attenuation of ultrasonic waves.

The paper explains these three issues in a practical simple way. By understanding these fundamental phenomena it becomes clear what the underlying implications to measurement are. For example, an USM may be linearized in the laminar / turbulent transition region produced by a volume flow rate at given flow conditions during a laboratory or field prover calibration. However, this transition zone is not fixed by a set volume flow range. The transition region is affected by various influences, such as installation affects, bulk fluctuations in fluid properties (e.g. temperature or composition changes), and local radial temperature / velocity gradients. Hence, a meter calibrated and linearized across one flow condition’s volume flow transition region can have significant flow rate prediction biases if the meter is subsequently operated in other flow conditions (which shift the transition region). It is a challenge to predict the point at which a field installed meter will be influenced by transition. Transitional flow adversely affects the path taken by an ultrasound wave, and hence the USM performance.

The paper discusses methods developed to improve the performance of USMs in and around the turbulent / laminar transition region. This includes the development of reduced bore USM designs which accelerate the local fluid velocity to mitigate the effects of transition, leading to better repeatability and lower uncertainty flow metering.

Introduction

This paper was conceived after an incident that made clear to me that there is a misunderstanding of transition and laminar flow. A USM was being tested in the Reynolds number range of 6000 to 10000 on oil and the meter was very noisy, with a high standard deviation (turbulence) output. The manufacturer was determined that the flow facility was at fault because transition, which I felt was the problem, only happened between around 2000 and 6000 and therefore it could not be transition causing the problem. Further they had managed to test he meter on water and that had shown no sign of transition at the higher Reynolds numbers. As we will see, Reynolds number is a great way to give an indication of the fluid mechanical changes experienced by a fluid machine, a flow meter, but it is not exact or precise. In fact it is often a very coarse indicator, because it depends on so many factors which in real life are not easy to define. Factors such as wall roughness, installation conditions and even additives in the fluid will change the onset and ending of a fluid process.

Most of us in flow measurement are used to living in high Reynolds number land, where changes in operation of a fluid machine are not dramatic. It tends to be at lower Reynolds number that changes of significance happen. When I and my colleagues first met the phenomenon of transition it was a real shock. At high Reynolds numbers for the meter being tested the average standard deviation of the outer paths is around 5% and in laminar flow around 2%, but for this meter the paths reached as high as 30%. This can be seen clearly in figure 1. In this case the transition region is clearly around the 4000 Reynolds number, later we will see with the same meter design on a different facility the transition region move to a higher Reynolds number.

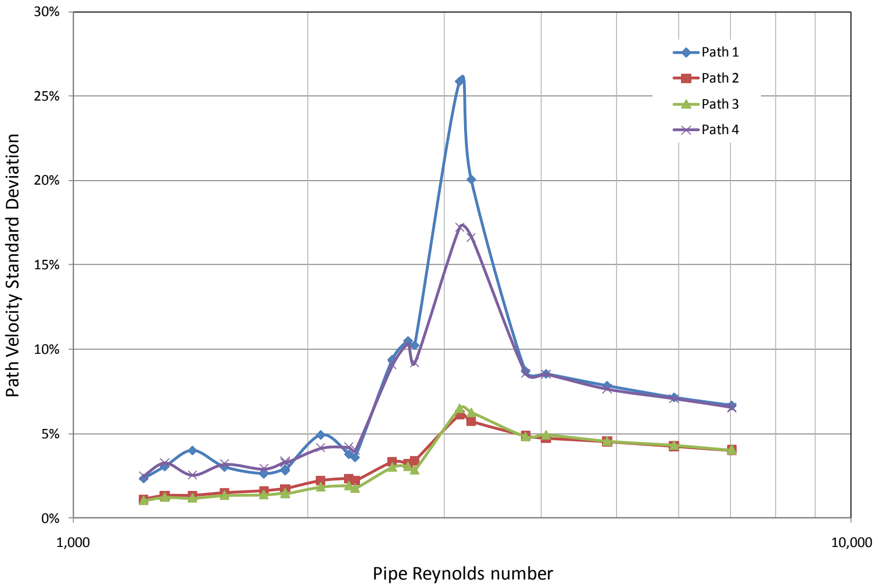


Figure 1 The Standard Deviation of a USM From Turbulent through Transition to Laminar

Once we had got over the shock of transition perhaps we would expect relief in the laminar region. The flow is steady, probably much better than turbulent flow except possibly for the large change in profile shape with small changes in Reynolds number. However, with a well-designed USM it would be expected that the effect profile changes would be resolved. Again, a shock, when calibrating USMs with varying temperature fluids we find that the calibration is unstable. Suddenly the simple calibration becomes a problem.

The issues are all related to the fluid mechanics of flow in a pipe and in the meter, and how the meter interprets these effects. The identifier is Reynolds number, this is the concept that gives the game away and tells us that we may have a problem.

Simple Fluid mechanics of Flow in a Pipe

This is not intended to be an exhaustive treatise on the flow in a pipe but a practical view of what happens and how it may affect flow measurement with a USM. Incompressible single phase flow in a long straight full pipe can be seen to have three main regimes defined by a Reynolds number range. Reynolds number is essentially the ratio of the inertia forces and the viscous forces, and tells us that at low Reynolds numbers viscous forces generally predominate and high values the inertia forces are the strongest. Transition happens at a balance point between the two. While Stokes was perhaps the earliest to realise the significance it was Reynolds whose paper in 1883 really nailed the significance, figure 2. He showed that the flow in a tube went through the three phases, laminar, turbulent and what we call transition. From these experiments he developed the dimensionless Reynolds number for dynamic similarity using the ratio of inertial forces to viscous forces. Reynolds also proposed what is now known as the Reynolds-averaging of turbulent flows, where quantities such as velocity are expressed as the sum of the mean and fluctuating components. Such averaging allows for 'bulk' description of turbulent flow. In other word although in turbulent flow the instantaneous flow can be in several directions there is a general flow downstream and an average profile, reference 2.

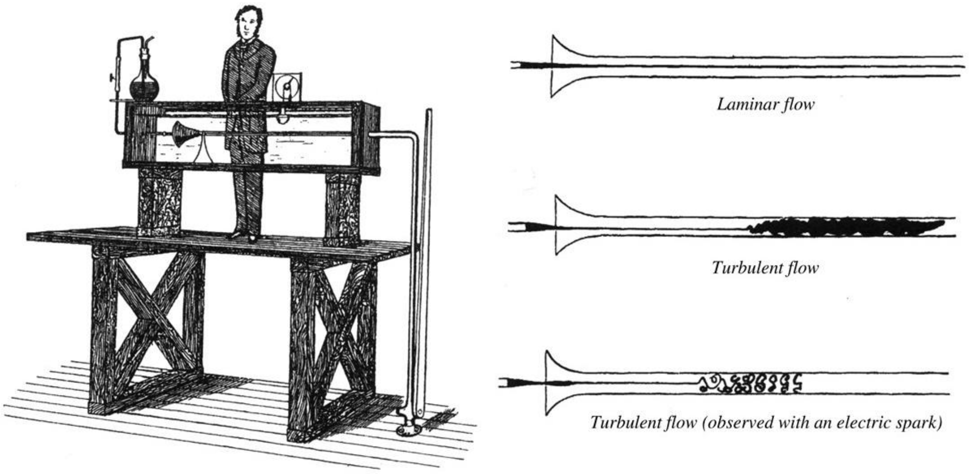


Figure 2 Diagrams taken from Reynolds 1883 Paper

We can therefore look at flow in a long straight pipe, for example, as a having several major characteristics. It has a general profile, which under fully developed flow conditions is symmetrical in the pipe and is essentially zero at the pipe walls and reaches a maximum at or near the centre. The shape in generally flatter at the centre for high Reynolds numbers and parabolic at low numbers. The flow at high Reynolds numbers is turbulent, flow in which the fluid undergoes irregular fluctuations, or mixing, in contrast to laminar flow, at low Reynolds numbers, in which the fluid moves in smooth paths or layers. In turbulent flow the speed of the fluid at a point is continuously undergoing changes in both magnitude and direction. The flatter profile in the turbulent region is largely the result of the mixing, which also results in smaller changes in profile shape with Reynolds numbers compared to laminar flow. Figure 3 shows how the ratio of the mean to the centerline velocity (the peakiness of the profile) varies across the Reynolds number range, there is a clear distinction between the turbulent and laminar regions.

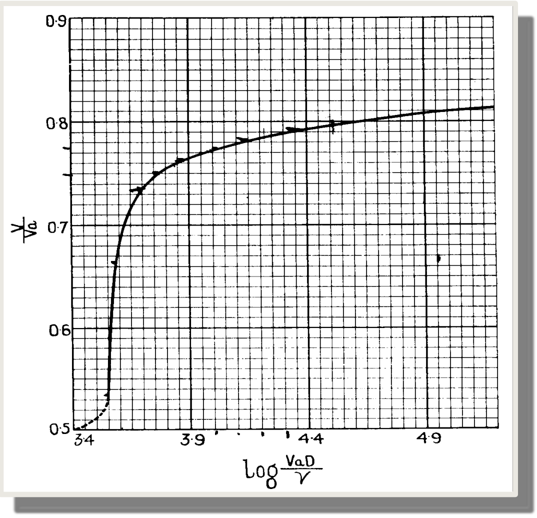


Figure 3 The Variation of Mean Velocity to Centreline For Fully Developed Flow in a Pipe (Reference 10)

Generally, therefore it is much easier design flow meters to work in the higher Reynolds number region. For many years this has been acceptable as many of the fluids we dealt with keep us up in the high Reynolds number area. Almost all-natural gas measurement is very high, certainly butanes etc are in this area. Low viscosity crudes for example found in North Dakota operate at reasonably high Reynolds numbers as well as kerosene’s and lighter diesels. It is the advent of the heavy crude oils and tar sands that have made life more difficult. Now fluids flows are moving down into the transition and laminar flow regimes and meters struggle. In fact all meters with the honourable exception of Positive displacement meters suffer anguish at the low Reynolds numbers. Turbine meters struggle, Coriolis meters become non-linear and USMs depending on the design can be problematic.

Where is Turbulence Sited

Turbulence is an instability generated by shear. The stronger the shear, the stronger the turbulence. This is evident in profiles of turbulence strength (u_{rms}) within a boundary layer formed by flow across a plate, Figure 4. The shear in the boundary layer decreases moving away from the wall and as a result the turbulence intensity also decreases. Very close to the plate, however, the turbulence intensity is diminished, reaching zero at the plate. This is because the no-slip condition applies to the turbulent velocities as well as to the mean velocity. This region is called the laminar sub-layer. The values in Figure 4 are normalized to the freestream velocity. When this is applied to a pipe, Figure 5, the effect is for the turbulent intensity to increase as it moves away from the wall to a maximum and then reduce towards the centre of the pipe. The maximum turbulent intensity is thus around 0.25 of the pipe radius in from the wall. Why does this matter, well for ultrasonic meters, particularly chordal meters some of the paths are sited within this region, and as we shall see that positioning gives some great benefits but also some real practical problems?

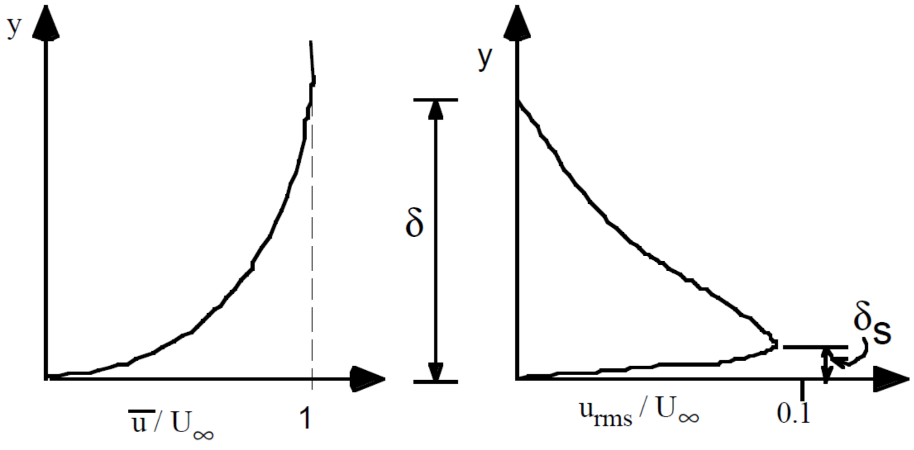


Figure 4 The Turbulence and Velocity Profile of Flow Near a Flat Plate (Reference 1)

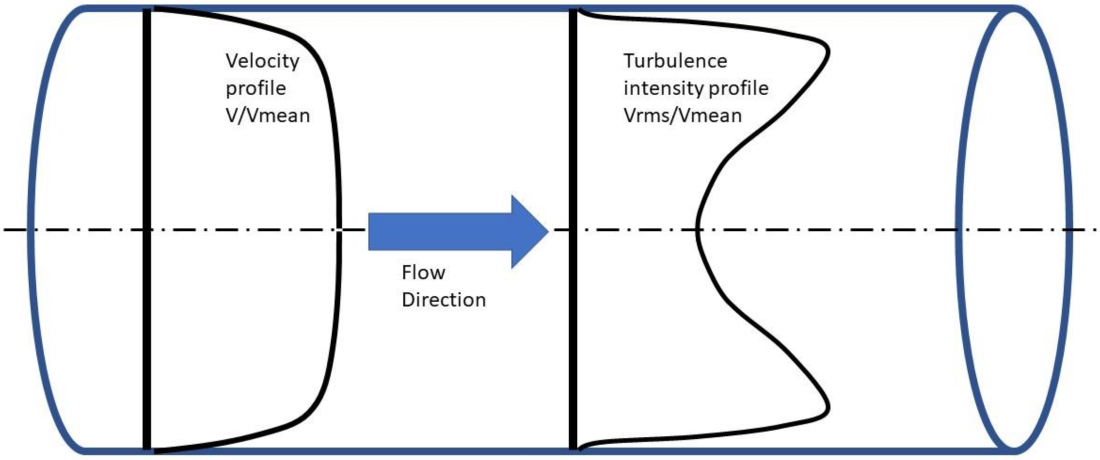


Figure 5 Turbulence and Flow profile Across a Pipe

What does Transition Look Like?

There are still a number of views on what transitions looks like particularly with respect to meters. There is no doubt that the flow at transition “switches” in some way from laminar to turbulent. Flow visualization using a dye or laser doppler detection shows clearly this effect over a small cross-section, Figure 6. Over a larger cross-section this tends to look like more of a “mush”, Figure 7. In fact It appears, Reference 1, that the transition takes several forms. The change from laminar to transition appears to be triggered by wave motion upstream, but is heavily influenced by the conditions, such as installation, roughness etc. At the lowest Reynolds number of transition, the flow is more in the form of “puffs”, small sections of turbulence, Figure 6. As Reynolds number increases the puffs split and form larger lumps referred to as “slugs”, Figure 6. Essentially the slug is a section of turbulence over a longer pipe section than the puff and is more coherently formed. The slugs get longer as the Reynolds number increases until the pipe is fully turbulent.

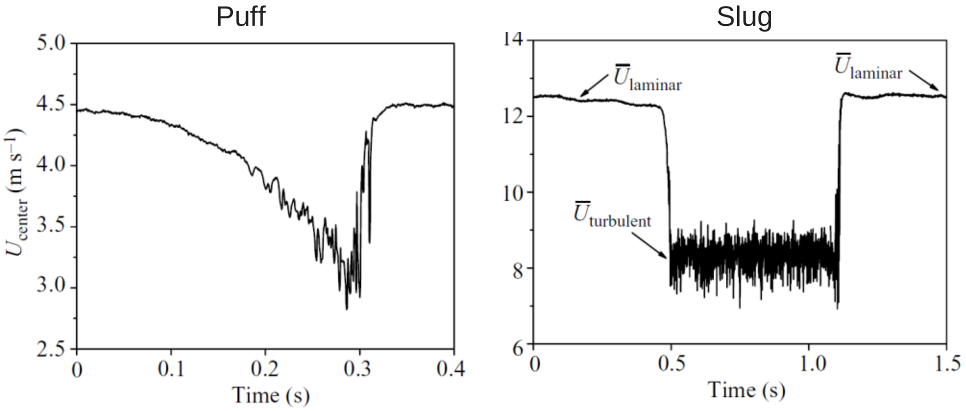


Figure 6 Puff and Slug Transition Formation in a Straight Pipe

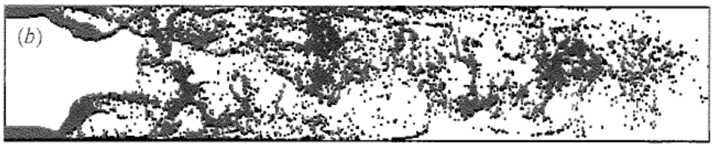
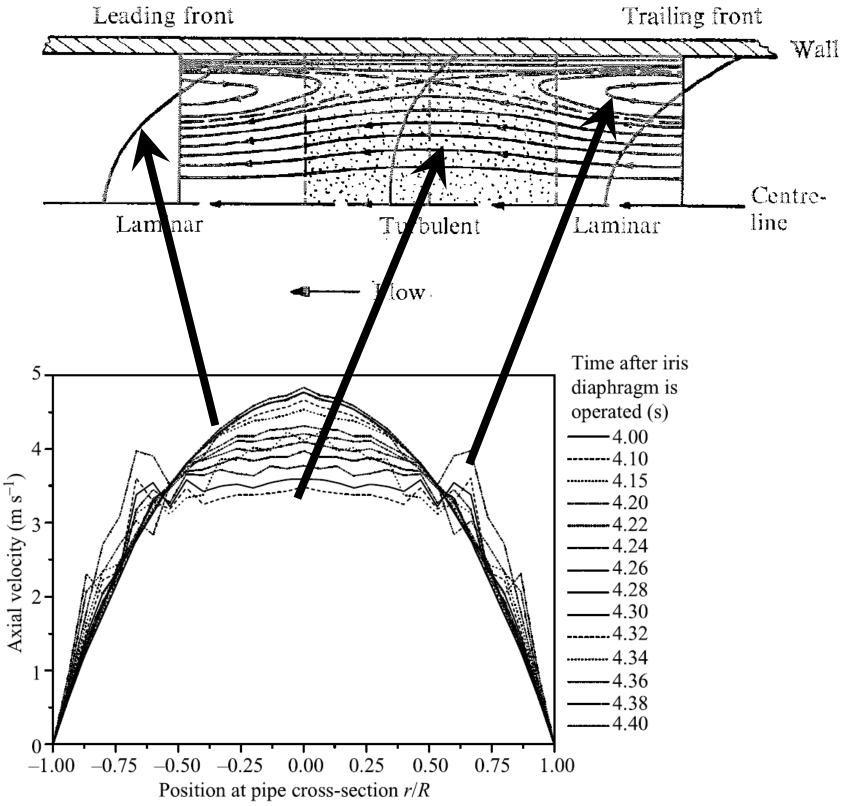


Figure 7 Particle Picture of Transition Flow

A further complication is the variation of turbulence and Reynolds number across the pipe. As previously noted, at all stages of Reynolds number there is a velocity variation starting at zero at the walls, and without any major disturbance moving to a maximum value at the centerline. A set of profiles is shown in Figure 8 for a “puff” flow, Reference 1, show that the profiles vary considerably from the normal fully developed flow, in this case showing what appears to be a vortex towards the pipe walls. It should be noted other forms of this profile have been seen, but in all cases the largest influence is towards the outside of the pipe. This as will be seen is of particular importance in the design of USMs, particularly chordal type meters. The position of the outer chords will be heavily influenced by the flow conditions nearer to the walls.



. Axial velocity as a function of different radial position r/R at different time after the iris diaphragm is operated at $Re = 2450$.

Figure 8 Profile Changes from Laminar through to Turbulence for a Puff Tansition

Why Should Laminar Flow be an Issue?

As stated previously it would be expected that with laminar flow a USM would be in very good shape. As shown in Figure 3 the profile changes rapidly with Reynolds number in the laminar region and this can give issues with correcting the meter if profile affects the calibration. The bigger, however, problem is better described as an application problem. In general, to allow efficient pumping it is necessary to heat the fluid to reduce the viscosity. Inevitably this will lead to a temperature difference between the inside of the pipe and the outside. For example, in winter on the Canadian part of the Keystone pipeline the outer temperature can be -40^{o}C and the inner heated temperature may be as high as 60^{o}C. In turbulent flow this does not represent a great problem because there is a natural mixing of the fluid due to the turbulence and so there is reasonably constant temperature across the pipe. With laminar flow, however there is almost no mixing. Unfortunately, most oils have very poor heat conductivity and so the heat tends to form a thin boundary layer of high temperature gradient oil around the inside of the pipe walls, Figure 9. The temperature gradient is essentially from the outside temperature to the inside.

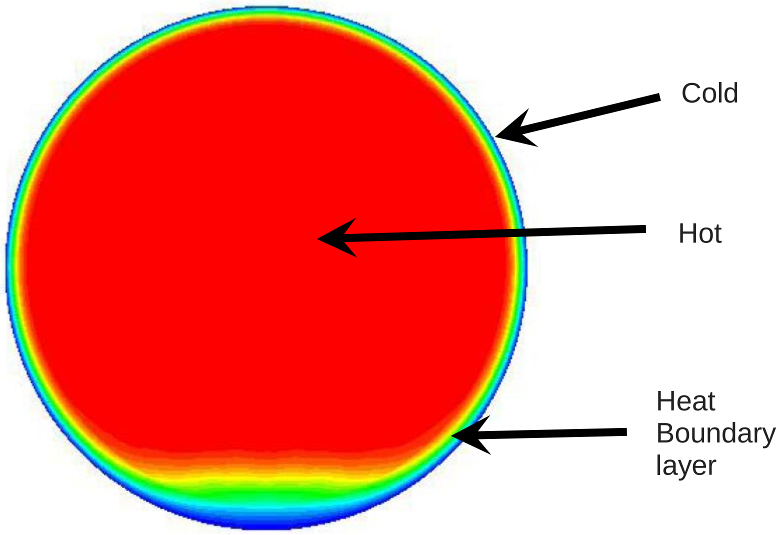


Figure 9 Temperature Variation Through Laminar Flow

At What Reynolds Number do these Events Happen?

If the meter design is influenced by the conditions in laminar and turbulence then it is clear there is also a need to know when these two events happen. Here we run into a problem, the end of turbulence and slide into transition is not constant but changes with installation, flow conditions and even the properties of the fluid. Similarly, with the change from transition to laminar. Reference 1 indicated that they for their experimental setup, which is very much more controlled than most of the applications we are dealing with, could go to 50,000 before changing from laminar to turbulent flow. This is exceptional but does show the potential extent of the variation. The data in Figure 10 taken from reference 2 shows very clearly the potential change in transition region, in this case two different sizes but similar design USMs at two different facilities. “The flatness data was taken directly from the ultrasonic meters and the Reynolds number was calculated independently based on measurements of flowrate and viscosity performed by the test laboratories. One meter was a 6-inch Caldon meter tested at NEL in the UK and the other was a 12-inch Caldon meter tested at SPSE in France. It can be observed that in the case of the 6-inch meter the transition occurred at Reynolds numbers between 3,000 and 5,000 but in the case of the 12-inch meter the transition occurred between 6,000 and 9,000 Re. Although pipe diameter may be one influencing factor in this case, it does not seem likely that pipe diameter alone is responsible for the difference in the critical Reynolds number (as this would be contrary to the whole notion of Reynolds number similarity). What is clear however, is that the critical Reynolds number is subject to various influences ….”, reference 2. The testing of the 12” meter was again somewhat of a shock, as we at the time were edging more to the idea expressed in many fluid mechanics books that transition is between 2000 and 6000 Reynolds number. The application specification took us right to the edge of this transition region without us realising this. The temperature variations at SPSE made it almost impossible to reproduce the lower flow calibration because if the test were carried out just after the pumps were started and fluid was cold, and the viscosity high the customers lowest flowrate (they were fixed on flow rate as a specification) took us into the transition region, as the tests wore on and the temperature increased the viscosity reduced and it was possible to obtain reproducible calibrations. **A point therefore to note is that if the meter is subject to changes due to the transitional region changes, and uses a correction based on Reynolds number, in this case Reynolds number would be too coarse to control the correction from application to application and from calibration to application.**

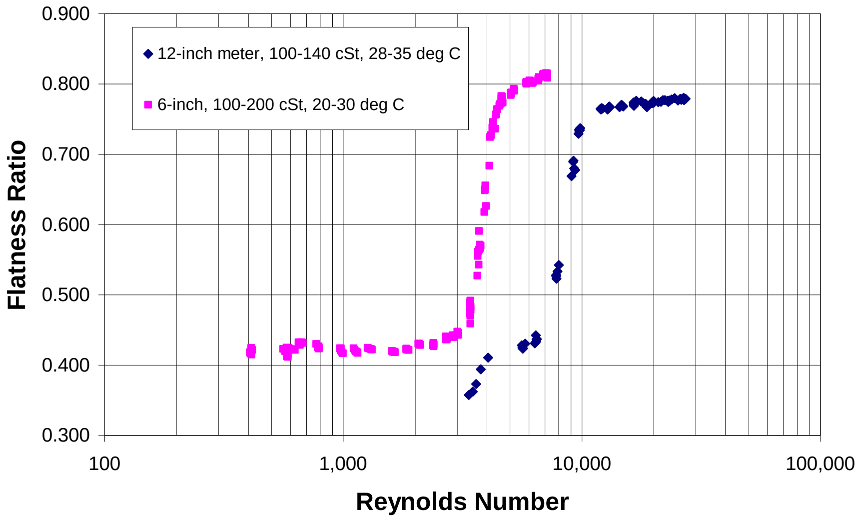


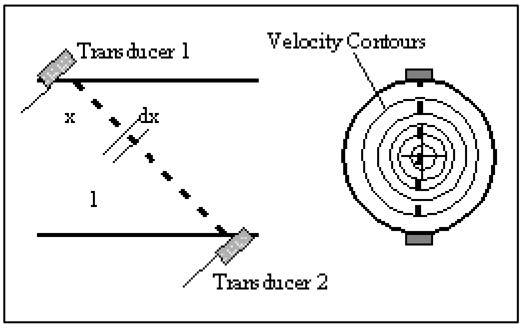
Figure 10 Change in Transition Region for Two Similar Design USMs

HOW DOES THE USM SEE FLOW PROFILE AND TURBULENT FLOW?

There are a number of configurations of USMs, from single path meters whose basic configuration is to fire sound through the centerline to multipath meters designed to make the meter less subject to installation changes. The detail of the basic designs and theory of operation has been dealt with by innumerable papers, but here I want to pick out some practical aspects to show how this type of meter deals with the flow in pipes.

A Single Path

If we consider just a single path meter, the sound which is fired through the flowing fluid at an angle has its sound speed modified by the velocity vector along the angle of sound transmission. Hopefully the fluid is moving axially along the pipe for this analysis. As the sound enters the fluid the sound velocity is modified continuously across the pipe by each change in fluid velocity, and the end result is a line integral of the velocities across the pipe, Figure 11. In this case we are assuming that the flow is constant and in a line parallel to the axis of the pipe. If we consider the case of the centerline transmission the end result would appear to be a transit time based on the mean velocity, but in fact it is a transit time biased by the centerline velocities, because when we look at the cross section we are only viewing a small sliver of area directly across the pipe, whereas it can be seen that the maximum contribution to the flow along the pipe comes from the velocities towards the outside of the pipe. This is the fundamental reason for the introduction, most tellingly by Westinghouse, of multipath meters.



$$Time_{1-2} = \oint \frac{x}{(c+v_x)} dx$$

Figure 11 Line Integral of Sound Transmission Across the Pipe

Multi-Path Meter Concept

The Westinghouse, the most comprehensive early method, concept was to take a number of paths and fire them as chords, and in this way, get a more representative description of the total flow at the cross-section being measured. They chose a method that determined the location of the paths using Gaussian distribution, for which there are a number of solutions, Figure 12. Others have chosen to use an experimental location for the paths and more or less paths, but using the same concept. There are a few exceptions such as the bouncing path meters to measure swirl etc. but we will concentrate on the chordal concept as the most common method.

Each path in the chordal method carries out a line integral along the chord they operate. The individual paths are then integrated with each other, each path being assigned a weighting factor to determine their contribution to obtaining the mean value. In general, the closer the outer paths to the outside walls the more sensitive the meter is to profile changes, and in general more capable of dealing with profile changes. The downside is that outside paths are then noisier which relates to the issues of turbulence in the pipe explained earlier.

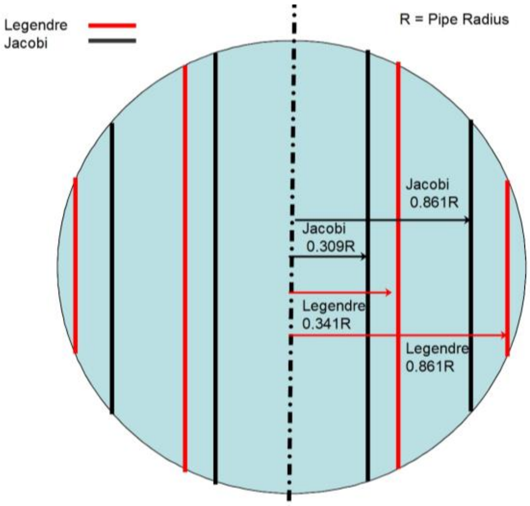


Figure 12 Examples of Path Spacing Positions

The Sensitivity of USM Paths to Turbulence

Within the suite of diagnostics is one often called “turbulence”. This is in fact the standard deviation of the individual paths as they fire through the flow. It is obtained by collecting a number of velocities (or times) at a nominally constant flowrate, and taking the standard deviation of the results. This does indicate the turbulence but also flowrate changes, instabilities, swirl and general noise of the meter (electronics etc). The USM is a sample type meter which samples the flow across the path. In the earlier description, we assumed that the flow was steady at each point. In fact when outside of the laminar region the flow across the path is a series of vortices with increasing and decreasing velocities along the line of the path. As turbulence is random and if it is small it might be expected that the effect would statistically cancel out. In fact there are always large lumps of low frequency turbulence that cannot cancel out and so we see the traditional issue of a poor short term repeatability compared to, for example, a turbine meter which uses inertia and mass to give some relatively constant RMS value of the turbulent flow. The higher the turbulent intensity the greater the standard deviation of the the paths. This can clearly seen in figure 1, where the outer paths have a higher STD than the inner paths.

The Sensitivity of USMs to Profile Changes

The single path meter we have already seen will tend to over read on a fully developed profile, and this overreading will vary with Reynolds number. It has to be corrected usually with some form of Reynolds number based algorithm. When the profile is distorted for whatever reason, installation, transition etc., the calibration will change and algorithm will fail to a greater or lesser extent dependent on the installation condition.

The concept of the multi-path meter is to try and reduce the effects of profile distortion by looking at more of the flow. It is physically impossible with current technology to analyse every part of the flow in a pipe, certainly with ultrasonics, and so we have to find ways to sample the cross section and then use methods to extrapolate the results. This resulted in the chordal type meters described, which use a number of paths and either an experimental or theoretical method to fill in the spaces to reduce the effect of profile changes. This works to a greater or lesser extent but is dependent on the design and path positions.

There are two issues with the standard chordal meter design:

- It is essentially only looking at one plane, Figure 13, and so asymmetry will tend to affect the meter performance depending on the axial relationship between the paths and the asymmetry (Data from the 32 Path meter, multi chordal meter). The degree of error will depend on the spacing and method of weighting the paths. A solution to this problem is to “move the paths around the axis of the pipe”. This is done effectively by the 32-path meter, which is essentially a set of eight four path chordal meters arranged around the axis of the pipe. Clearly with the right weighting a better indication of asymmetric flow will be obtained.

- As shown in Figure 14 a large part of the contribution to the overall flowrate comes from the velocities towards the pipe walls which even the chordal path meter misses. While the extra paths give more information on the profile than for example the single path, the location of the outer paths will be critical in determining how well the meter operates with not only asymmetric but also symmetric profiles. For example, swirl profiles can be symmetrical but very different in centre to a fully developed profile. The USM can tell there is a difference, but because so much of the change is related to the outer flows the meter may still not be able to resolve the actual volume flow even with a good cross path method of removing the cross flow induced by the swirl. The further the outer paths are towards the wall, the more representative of total flow is likely to be the answer. As will be shown, however, this can lead to other issues, particularly in terms of repeatability due to turbulent noise and also in the transition region.

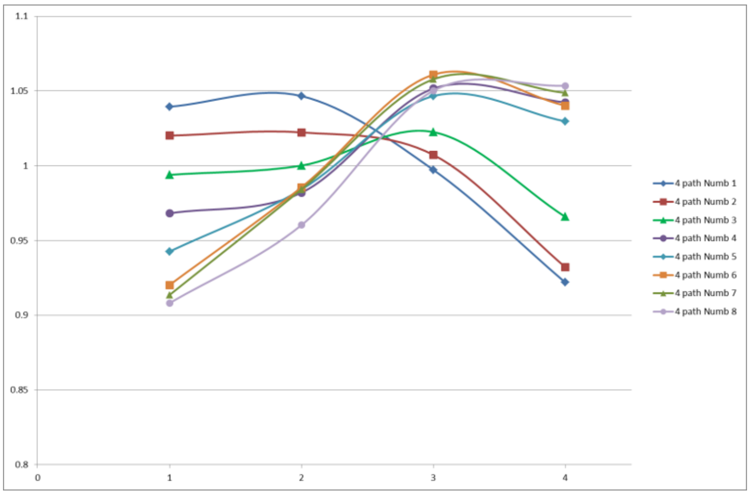


Figure 13 The Variation of Profile In Different Planes Downstream of a Swirl Source

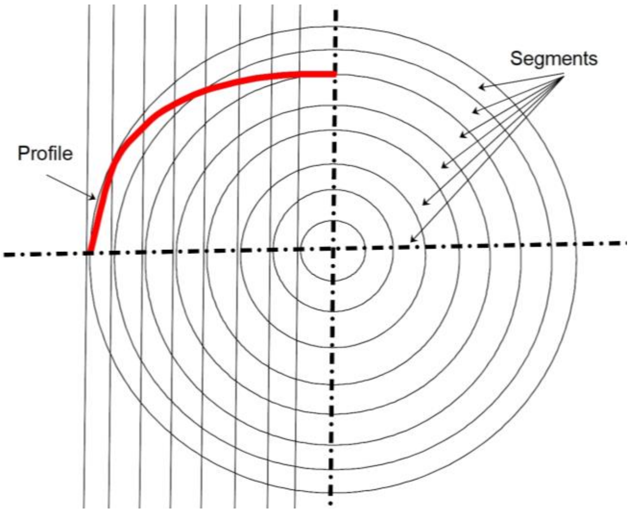


Figure 14 Diagrammatic Representation of the Segmental Areas and Profile

Having described the effect of profile with fully developed and distorted profiles on USMs how does this then tell us about the effect through transition? We have seen how the outer paths in chordal systems contribute to the measurement of the flow. The theory of the weighting unfortunately is based on a linear division of the area of the pipe not radial, and is therefore still not able to see all the influence of the outer velocities, as the line integral will still only see the outer wall velocity as a small part of the transit. The further out towards the wall the more the outer paths will see of the outer velocities. A good example of this is the two solutions to the gaussian method of placing the paths. The Legendre solution places the outer paths closer to the the pipe walls and results in a relatively linear calibration on a fully developed profile pipe flow above around a Reynolds number of 10,000. It also does a better job of dealing with asymmetry. The Jacobian solution in less linear, shown in Figure 15 and not as good at dealing with installation conditions. However, as we shall see, in transition and for repeatability the Jacobian is better is more effective.

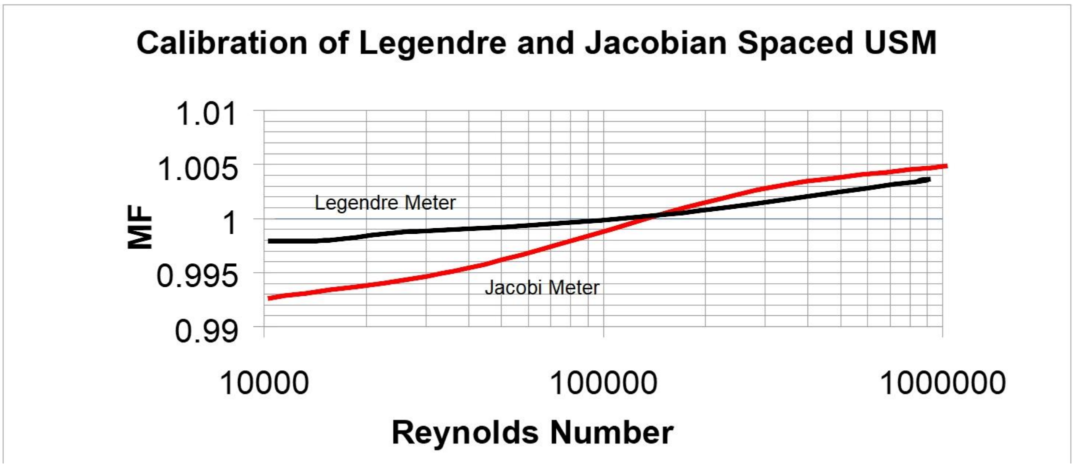


Figure 15 Legendre and Jacobi Calibration Curve for 8” Meter

Flow Noise (Turbulence) Effect on USMs

It is not the purpose of this paper to criticize one method or another but to point out why we see issues in the transition region and laminar region. If we therefore look at an arbitrary positioning of, for example, a 4 path meter superimposed on the turbulence picture in a fully developed turbulent condition we immediately see our first potential issue, the outer paths will sit around the high turbulence area, Figure 16.

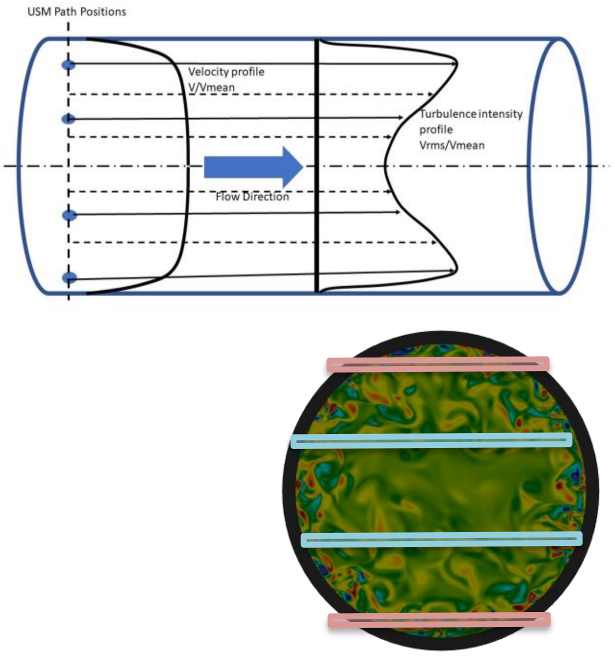


Figure 16 Position of Different Path Positions in Relation to Pipe Turbulence Levels

Depending on the design, and in particular the positioning of the outer paths the noise level will vary greatly. As will be seen this will give rise to further issues during transition.

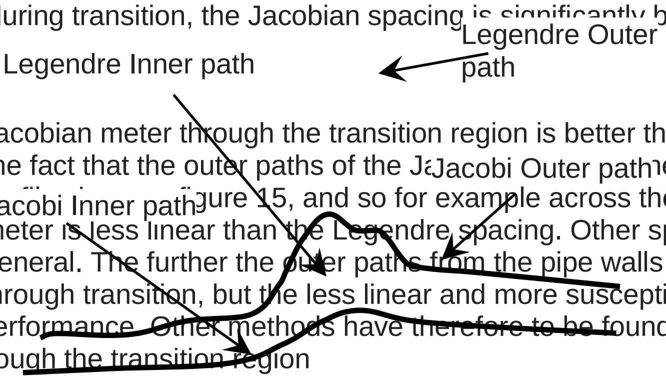
THE EFFECT OF TRANSITION ON A USM

We have seen that a USM is very dependent on the design for its ability to cope with changes in profile. They are generally better than most meters but as a rule the further towards to pipe walls of the paths the better the meter is at dealing with profile changes. In transition this is not he case because as was seen the outer paths are sitting in what appears to be a reverse flow vortex formation at some point between the laminar and fully turbulent sections. This places on the outer paths a series of extreme changes which results in the paths “seeing ” large swings in the velocities, even to the point of a reverse flow. If the paths are located more towards the centreline then the chances are that these large changes are less violent. In fact an early patent reduced the large variations by switching off the outer paths and just allowing the inner paths to operate when the meter was in the transition region. A further issue is the rapid changes now seen in turbulence level. At one extreme there is almost no turbulence, the laminar section, and at the other is a fully turbulent flow. Remembering that the end result of the data obtained from the USM is a set of samples which are averaged by some chosen method with time. If there are violent swings in the samples the standard deviation of the paths will increase and the repeatability of the meter output will increase in line with the standard deviation. The average calibration at each point during this process is likely to be different to that seen at turbulent and laminar, and there will be a shift in the calibration.

Here is the next issue, there will need to be some compensation for the change in calibration during transition, so how do we indicate that the meter is in transition. The obvious answer would be to use Reynolds number. However, as we have seen the range over which transition can happen varies with so many conditions, even in the same application. So for example if a meter is calibrated at a facility and "linearised" to go through transition at the facility what is to say that this will be adequate on site? The issue will obviously depend on the design but in an extreme can lead to large errors from the meter on site. Perhaps to a degree at least the issue can be alarmed by looking at the Standard deviation (Turbulence) diagnostic, particularly with reference to the outer paths.

Can the Effect of Transition be Mitigated

Clearly from the issues raised the position of the outer paths becomes critical to the influence on the meter performance. As stated one early solution was to switch of the outer paths and rely on the inner paths. This solution works but leaves the possibility of an increase in uncertainty during the time the paths are switched off. Moving the paths away from from the area of outer instability is a solution, and certainly it mitigates the the noise effect to the point where measurement is more stable, this can be seen in the two examples shown in figure 17. The Legendre spacing which places the outer paths closest to the walls experiences the largest variation in signal standard deviations during transition, the Jacobian spacing is significantly better and in general repeatability of the Jacobian meter through the transition region is better than for the Legendre. This is balanced by the fact that the outer paths of the Ja[illegible]ner from the walls is more influenced by [illegible]gure 15, and so for example across the Reynolds number range the Jacobian meter is less linear than the Legendre spacing. Other spacings fall between these two values in general. The further the outer paths from the pipe walls the easier it is to obtain good results through transition, but the less linear and more susceptible to pipe induced profiles changes in performance. Other methods have therefore to be found to make a meter work successfully through the transition region



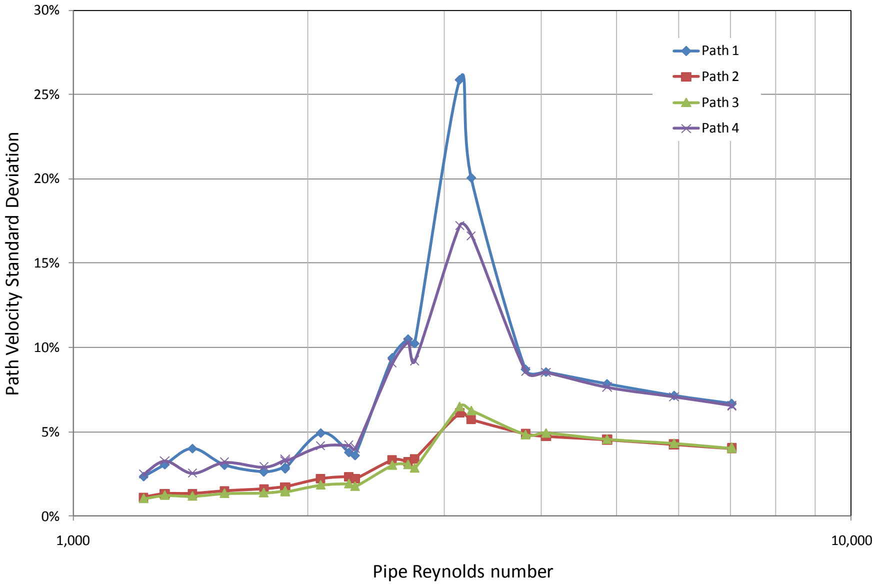


Figure 17 The STD of Paths for Legendre and Jacobi Spacing

The Multi-4 Path Solution

One method that reduces the effect of the “noise” but is able to retain a high ability to deal with installation effects is the 32 path meter which consists essentially of eight 4 path meters rotated axially around the meter tube, figure 18. Two of the 8 sets of 4 paths are shown in red and black for clarity, the rest can be seen forming a rotation around the axis. It will be noticed that the outer paths are further inboard than for the standard 4 path meter with a consequence the STD of the path data is able to move through the transition zone with very little increase in noise, and hence retains repeatability when proving, figure 19. As stated previously moving the outer paths inboard for a single four path meter leads to a reduced ability to deal with varying installation conditions. In this case the extra paths now compensates for this lack of detail obtained from the profile close to the pipe walls by combining the data in an axial mode around the meter section. The amount of extra data now available for this can be seen in figure 13, the profiles obtained downstream of a double bend out of plain, that is with swirl. More detail is available to determine the effect of profile on the meter, particularly towards the pipe walls, because of the extra number of paths compensating for the fact that the paths are located more inboard than normal.

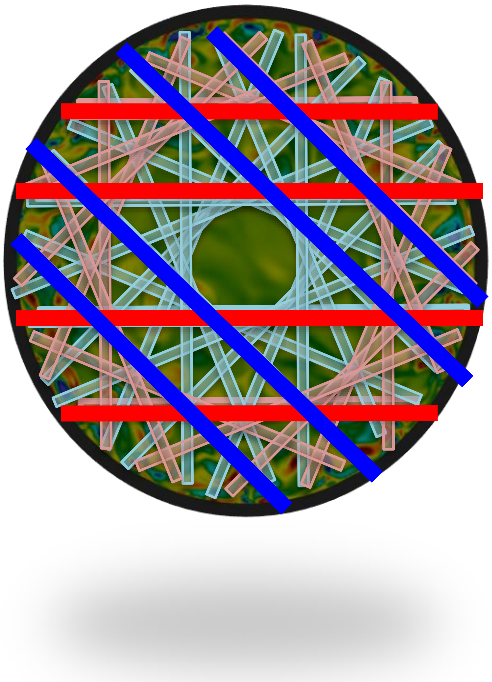


Figure 18 Path Configuration for 32 Path Meter

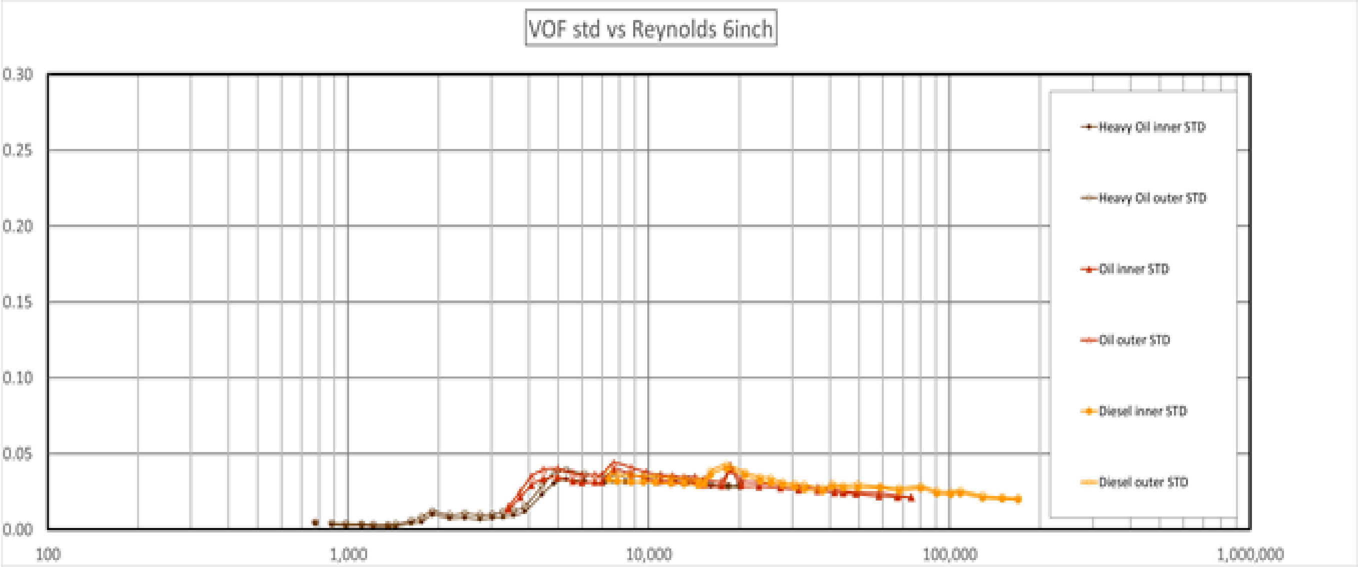


Figure 19 STD of All Paths for a 32 Path Meter

Reduced Bore

The other main solution to moving through transition is to reduce the bore of the meter section. This is a fundamental fluid mechanical solution that comes straight from aeronautical testing. Windtunnels use a reduced section to help reduce two main problems, they reduce turbulence levels and they control the flow profile. Immediately after a smooth reducer the turbulence level is controlled and reduced, thus the switching from a laminar state to turbulence is far less violent. On top of this the reducer always forces the profile in the reduced section towards a flat profile whatever the inlet flow. The only exception is the presence of swirl which can be aggravated by the reduction. Figure 20 shows a typical set of standard deviations for a reduced bore meter with a nominal 0.6 diameter ratio reduced bore. With this design there are small indications of transition but the STD does not go above 6%, and so the repeatability remains stable through the regime.

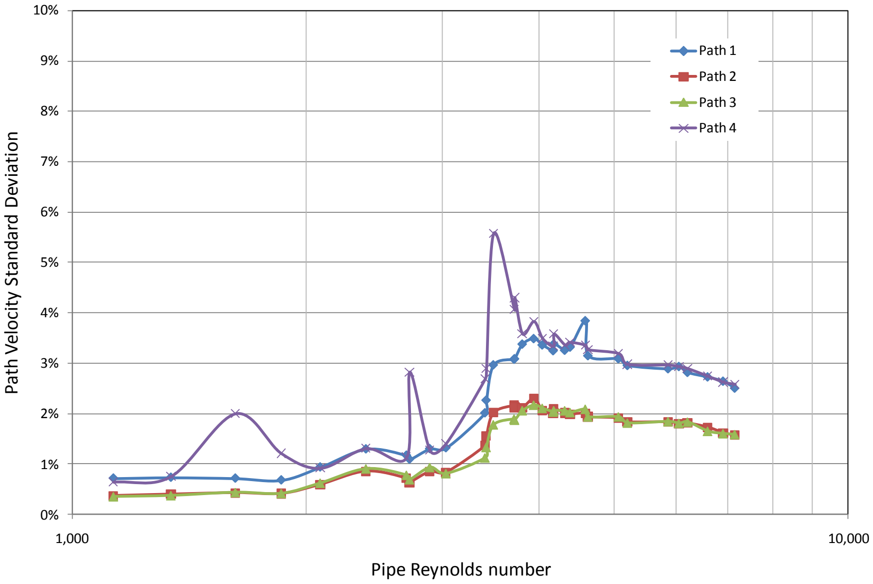


Figure 20 STD of Paths for a Reduced Bore USM

The downside of this method is that it loses one of the main attributes of a USM, it has a significant pressure drop, but certainly allows the meter to be used through transition with negligible effect on the performance.

LAMINAR FLOW AND USMs

It was noted in the description of laminar flow that there are formed temperature gradients. This is an **application** issue, because laminar flow usually implies a high viscosity fluid, and to ensure efficient pumping the oil is usually heated to reduce the viscosity. There is there for often a large temperature difference between the outside of the pipe and the inside. As stated the thin layer of varying density is formed around the pipe, and in the case of a USM will cover the transducer pockets. For the ultrasonic meter it represents a refracting barrier to the sound, the different densities acting on ultrasound in a similar way light refracts through an air glass interface. The time of flight and hence the calibration of a USM is dependent on the transmission angle of the ultrasound. The refraction changes this angle resulting in at best a change in calibration, figure 21 or at worst the complete loss of the signal as the ultrasound misses the the receiver. In figure 21 the ambient temperature is substantially constant but the fluid temperature is changing.

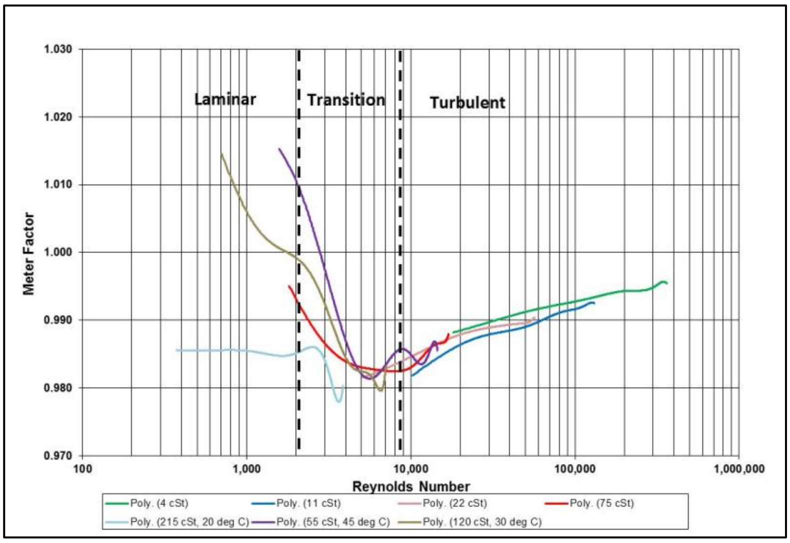


Figure 21 Effect of Changing Fluid Temperature in the Laminar Region

Solutions to Temperature Gradient Problem

The solutions to the problem, as it is an application problem are basically application orientated. The best solution is generally to heat trace the pipe, to keep it close to the fluid temperature. Insulating the pipe may help, but may also eventually fail if the pipe temperature eventually reaches the outside temperature. If the outside is hot and fluid cooler, this is generally a sun issue, and shading the meter will help alleviate the problem.

Laminar Profiles

As stated the laminar flow profile is much”sharper” than the turbulent profile, and changes rapidly with Reynolds number. This is not a problem for a USM that can deal effectively with profile changes, but for example a single path meter will see a significant change in the calibration unless the method of compensation for Reynolds number is very effective.

CONCLUSIONS

As a general comment measurement at low Reynolds numbers is difficult for most meters. For USMs transition and laminar flow measurement present some real challenges. It is possible to overcome these challenges, but the user should be very aware of the possible issues that may confront them. Further do not fall into the trap that the issue is confined to only a small and specific range of Reynolds numbers, this can and will change with application. The corrected calibration through the transition area may not transfer from calibration to site with a consequent change in calibration.The best solution to the transition issue is a meter that has a minimal change in performance through transition. The issue with temperature gradients in laminar flow is a feature that will effect all USMs as it is a fundamental application problem. The soluions are to heat trace or possibly insulate the piping.

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