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Reynolds Number, the Correct Calibration, Characterization and Proving of Flow Meters

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ABSTRACT

The flow world has forgotten the importance of Reynolds number for determining the performance of flow meters. Many users and even manufacturers do not understand the meaning or implication of this concept. The implication of the reality that flow meter performance is dictated by the Reynolds number is that meter manufacturers with in-house water calibration laboratories have to send their meters to third party independent calibration facilities in order for many of their meters to be properly calibrated for their applications. In turn operators have to pay more for a correctly calibrated meter. This has resulted in some cases as total denial by the flow meter manufacturers who do not want their meters to be dictated by Reynolds number, with the consequent extra calibration expense. API MPMS chapter 4, one of the better standards assiduously avoids any mention of Reynolds number by saying the meters should be reproved if there is a significant change in viscosity. This implies Reynolds number but does not explicitly use it. We know that all meters used on gas and liquid measurement, Turbines, Coriolis, USMs, differential pressure meters have variations in their calibration determined by Reynolds number to a greater or lesser extent depending on the type and design. Previous papers have described the methods and issues of correcting for Reynolds number and pointed out the pitfalls, which can cause unexpected bias, with consequent financial implications. This paper builds on the issues to show with real data the implications of not considering Reynolds number when designing calibrating and operating meters. It further points out the flaws of using flowrate, velocity, correction methods, where Reynolds number is the predominant physical property determining the meter performance. Finally the paper discusses the pitfalls attendant on using extrapolation, when there is little or no knowledge of the meter performance in the extrapolated area. A number of examples will be shown of the effect of not recognizing the potential problems.

1 INTRODUCTION

This is the culmination of series of papers designed to show used in the Hydrocarbon industry are influenced by Reynolds number, and the effect that ignoring this phenomena can have on their performance. For many years it has been accepted that the installation of meters is of primary importance when using flow meters. The installation effects can be changes in flow profile which will effect some meter types or mechanical installation which will affect others. What has not been accepted universally is that before even the installation there are basic fluid mechanical issues, particularly Reynolds number which must be confronted to obtain reliable and low uncertainty measurement. When combined the installation effect and Reynolds number become a complex interacting set of variables that make the understanding of how meters work under site operating conditions very difficult. Some issues can be easily resolved, orifice plates installed back to front, control valves immediately upstream of the meter, blockage of the meter or flow conditioner etc. But many discrepancies in measurement turn out to be complex, not obvious and sometimes insoluble. Many of these complex problems ultimately revolve around how the meter really operates and in particular the effect of Reynolds number on the process fluid, the meter and the method that the meter uses to combat the consequences of Reynolds number on the meter operation. The only sensible way around Reynolds number is first to accept that it is important, then to find stable and acceptable methods to correct the meter. It generally starts with a good calibration, representative of the flow conditions to allow for a good characterization of the meter, and then some method to carry this characterization successfully into the field. Making assumptions about the characteristics of the meter curve brings us firmly into the area of extrapolation. Fluid mechanics is a graveyard of best intentions, where we have assumed that fluid phenomena continue to react in a way that is simply predictable only to find that changes happen to totally discredit the concept.how all of our main meters

2 REYNOLDS NUMBER

This has been defined many times, and in previous papers on the subject but to clarify it again, it is defined as the ratio of inertia forces in a fluid to the viscous forces. At low Reynolds numbers the viscous forces predominate and at higher Reynolds numbers the inertia forces are in the ascendency.

The simple equation that determines Reynolds number is given in equation 1, showing that it is a function of a characteristic dimension D, usually in the case of flow measuring taken as the pipe diameter, the fluid velocity,v, and the kinematic viscosity,☐, the ratio of the absolute viscosity to the fluid density.

$$R_D = vD/\vartheta \text{.........}1$$

As a general rule but not always true the changes in fluid mechanics are greater at low Reynolds numbers than high. So at low Reynolds numbers' particularly through transition, as the fluid becomes laminar, and for example the flow profile in a pipe changes rapidly as the Reynolds number changes, shown by the ratio of the mean to the maximum velocity of the profile, [1] figure 1. At higher Reynolds numbers the fluid is turbulent and the profile changes flatten out. The change ratio is usually seen as around 1% per decade. Figure 1 shows also the change in profile experienced by a four path ultrasonic meter, as can be seen the curve is very similar.

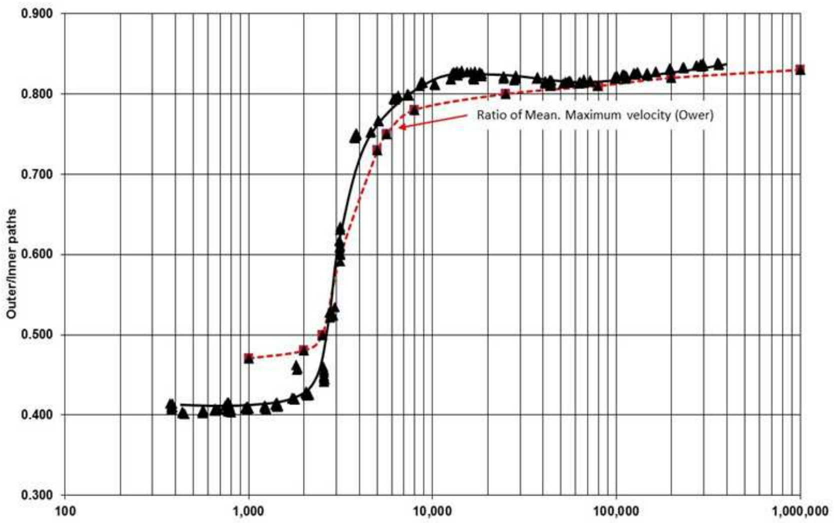


Figure 1 - Variation in Flow Profile velocity Ratio with Reynolds Number

As stated at higher Reynolds numbers generally the forces induced by fluid phenomena are more stable and so for example Gas Ultrasonic meters tend to be more linear with Reynolds number, and other factors such as Mach number become an issue. Be aware that everything is relative. As Gas meters begin to claim better and better performance there is still an underlying Reynolds number deviation, which needs to be corrected. Some manufacturers assume the non-linearity is velocity, it is not. With the current specifications for gas meters this probably works without taking the meter outside of the specification, but when the claims get to the level of their liquid cousins this will become more of an issue.

An idea of the real span of Reynolds number as it effects the natural world is shown in Table 1, giving some feel for the vast expanse of Reynolds that nature has to resolve methods of motion to accommodate.

	Reynolds number
A large whale swimming at 10 m/s	300,000,000
A tuna swimming at the same speed	30,000,000
A duck flying at 20 m/s	300,000
A large dragon fly going 7 m/s	30,000
A copepod in a speed burst of 0.2 m/s	300
Flapping wings of the smallest flying insects	30
An invertebrate larva, 0.3 mm long, at 1 mm/s	0.3
A sea urchin sperm advancing the species at 0.2 mm/s	0.03
A bacterium, swimming at 0.01 mm/s	0.00001

Table 1 Spectrum of Reynold Number in Nature

Usain Bolt averages a Reynolds number of around 800,000 during his Olympic medal runs!!!

The really big problem with Reynolds number is that for complex fluid machines there are a variety of Reynolds numbers affecting the performance. This is because we choose to take a single dimension and velocity in the equation, usually in the case of flow metering the diameter and mean pipe velocity. Changes however appear at different Reynolds numbers if we do this. For example the simple orifice plate goes through a variety of changes, the change in profile, based on diameter, change in the boundary layer on the plate surface, this should be the plate length to the throat, but we use diameter again, and finally the changes in the separated boundary layer forming the jet. This should be some function of the jet, but again for convenience we use pipe diameter. Similarly with velocity. If the right dimension and velocity were used for each process then they would all happen at similar Reynolds number, but by virtue of using a single dimension they happen at different Reynold number values resulting in the apparently complex shaped curves with several changes across their range for many of our meters produce during calibration.

The issue of whether we see changes happen at higher Reynolds numbers can be seen in the case of the vortex meter. The majority of meters now have sharp edges to define the separation of flow from the bluff body. Early designs and patents concentrated on using a circular cylinder, because it was an easy shape to manufacture. Unfortunately if we look at the calibration of a circular cylinder vortex shape we see that there is a change in the calibration, Strouhal number, at a high Reynolds number, figure 2. At the low Reynolds numbers the change is due to the separated boundary layer changing from laminar to turbulent. At the higher Reynolds number the boundary layer on body itself changes from laminar to turbulent. The layer now has more energy to battle against the adverse pressure gradient around the body, and so the separation point moves, changing the vortex frequency. The use of sharp edges stops this effect, by determining physically the separation point.

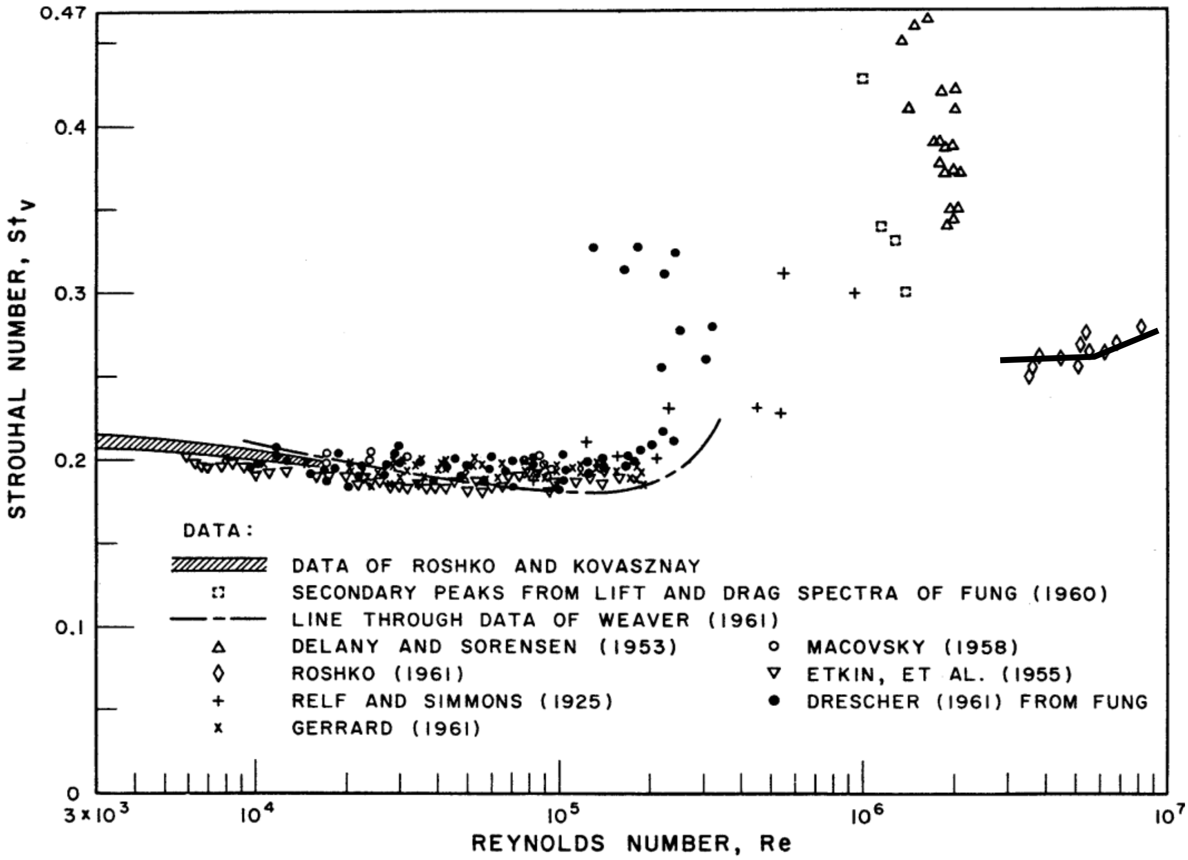


Figure 2 - Change in Calibration of a Circular Cylinder Vortex Meter

The major issues to note about Reynolds number are:

- **All meters are beholden to Reynolds number in some form or another.**
- **It can jump up and bite you if you have not done the proper investigation into its effect on a product, for example for years it was said that the Coriolis meter was not subject to Reynolds number, and now we know that it is a mere mortal like the rest of other meters in this respect.**
- **Reynolds number effects are different not only for different meters types, but also designs and even within the same design, largely because it is difficult to manufacture meters that are so identical that Reynolds number effects are exactly the same when we are trying to produce low uncertainty measurement.**

It should be emphasized that Reynolds number is not the only effect, bearings, resolution velocity effects can all contribute to meter errors.

3 HOW DOES THIS RELATE TO FLOW MEASUREMENT

All of this is great in theory but how does this effect measurement? The issue is not a new one, Reynolds number correction of meters goes back to the very earliest days of flow measurement as an accepted need and science. Looking at the early standards for differential pressure meters Reynolds number correction is an essential part of the meter performance. In BS 1042, the earliest standards relating to differential pressure measurement clearly show in graphical form the corrections, figure 3, and further discuss the increase in uncertainty.

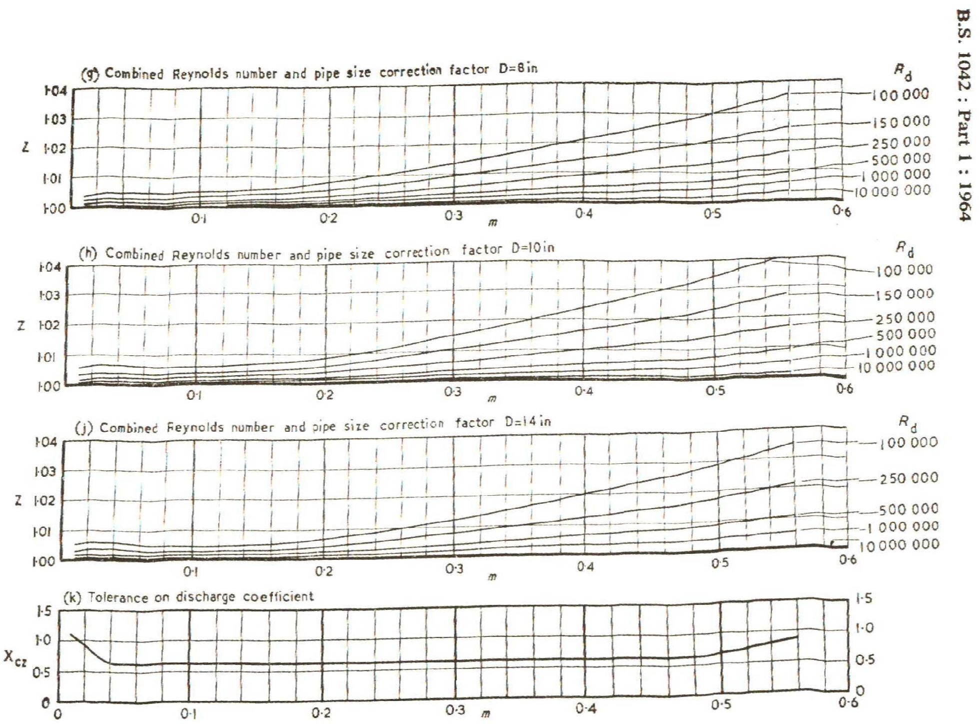


Fig. 41. Data for orifice plate with flange tappings—*continued*

Figure 3 - Reynold Number Correction of Orifice BS1042

When presented in this form it is easy to see the correction, particularly as we also then had to do a hand correction and so its relevance to measurement was very clear, now we have a complex equation used in most times in a computer and so the relevance is less obvious. More often than not now the extra uncertainty that results from the calculation of Reynolds number and the shape of the calibration curve is entirely forgotten. In fact it is now ignored completely largely because the corrections are hidden entirely within a "black box" and the methodology is hidden. Without knowing the methodology it is largely impossible to determine any extra uncertainty, or even how good the method is at correcting the changes due to Reynolds number.

In fairness there is more openness within the gas measurement industry. The methods used to calibrate and linearise Gas USMs are very clear, in fact CEESI now does the corrections for most manufacturers, and in fact the calibration is shown as an "as found" and as "as left" ,figure 4, so that it can be easily seen how much correction is applied and how it is applied. Many manufactures still use velocity as the base correction which is not correct, but at least from the calibration data feasible to understand and calculate the possible extra uncertainty.

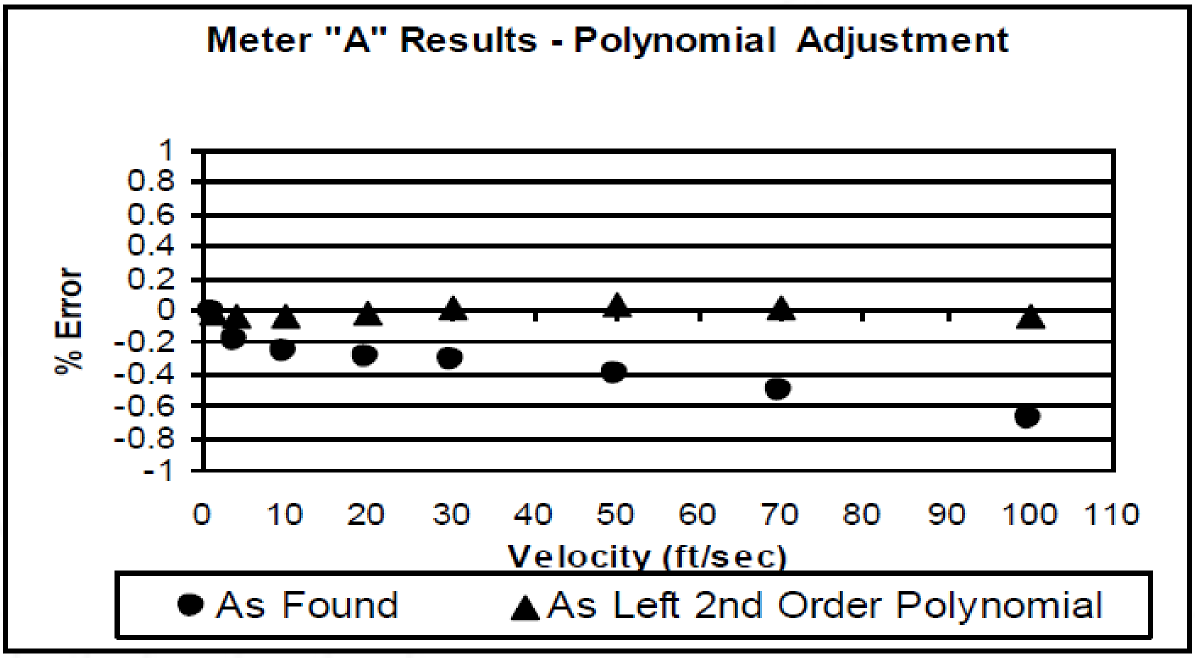


Figure 4 - Correction of a Gas Ultrasonic Flow meter using a Polynomial Velocity Fit.

It should be noted that for Gas USMs the method of calibration is laid out in standards, for example AGA 9. They call for an "as found" and "as left" calibration. The "as left" is after the corrections are applied. It should be noted, however, that while at least they call for both bits of data to be supplied, unlike the graph in figure 4 they only call for two or three points for the "as found", when this is the curve that is really important piece of information to the user!!

The real difference between the liquid and gas methods seems to have come from history. Gas meters have very little opportunity for calibration checks on site, whereas for liquids there has for many years been the ability to prove the meter, and hence check the meter calibration on site. This has developed a mentality that proving will solve all ills, and that the minimum is required for the calibration of the meter before it is installed. This as will be shown has led to some potential errors in measurement, and lax procedures that could be costing metering uncertainty.

On the liquid side the methods of correction is generally hidden, and even denied either explicitly or by non-discussion. Most USM manufacturers, although there are still some exceptions, recognize the need for a proper calibration that covers the operational parameters, most importantly Reynolds number, of the meter, figure 5. To ignore this means that the calibration must be extrapolated, and either the curve is ignored or assumed. Particularly at lower Reynolds numbers the curve of a USM can, depending on the design, produce large linearity errors. Machining does not easily reproduce the detailed shape of for example the transducer ports, and so the calibration curve will change in detail from meter to meter. Remember we are looking for a total uncertainty in the order of 0.2% for liquid custody transfer meters, and so these small changes will matter, and proving does not necessarily solve the problem. Perhaps the biggest problem is the methods used. These have been previously described [1], and can still be very fragile.

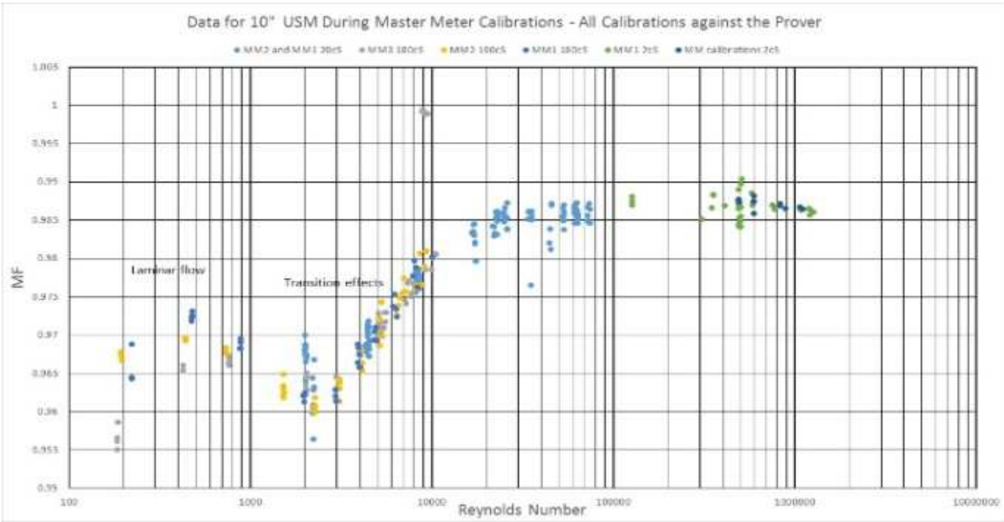


Figure 5 - Calibration of a 10" 4 Path USM

The same is true for the Coriolis meter, but probably more hidden than for a USM. It took over 20 years to discover the fact that a Coriolis meter is subject to a Reynolds number non linearity at low Reynolds numbers, figure 7. Once eventually found it would be expected that we would have heard about solutions to the problem. These may be design, for example tests seem to show that lower frequency, smaller meter seem to have less susceptibility, or how the problem is being solved. Only one manufacturer has shown their solutions. Others must be solving the problem but are not willing to share the methodology. This leaves a feeling of suspicion as to how the method works. Further the majority of Coriolis meters are calibrated on water, which will not allow for anything other than an assumed correction for the meter at low Reynolds numbers.

The turbine meter has now several detailed descriptions of the method used to linearise the meter [2]. Particularly Helical bladed meters are usually now calibrated on hydrocarbon, to be able to improve the linearity of the meter under operational conditions. As described they can be modified fluid dynamically to account for the eccentricities of the calibration, and bring the curve close to linear relationship over the operational range.

4 PROVING

Proving should solve the problem! Proving is a very effective method for ensuring that the meter calibration is corrected for the vagaries of site installation. It does however present several practical problems. If as we see meters are non-linear with Reynolds number and not corrected properly we are left with several scenarios:

1. If the flowrate is nominally constant but the viscosity changes, for example due to ambient temperature then:
   I. Using the API philosophy of proving every time there is a change in viscosity, but how often should it be proved? It is not clear as to how much and how often this should be done?
   II. In most cases in the US, proving is done by contract prove companies, maybe every 3 months, how do you get the prover company to come in for example every day. In the Northeast of USA on in winter the temperature can change from day to day up to 20°C. Even between night and day this can vary by the same amount in parts of the world. How many times do you prove?
   III. You could correct it by proving against Reynolds number, but few manufacturers allow you to get into their electronics and put in the correction.
   IV. There are now some Flow computers that allow for Reynolds number correction, but how do you know the Reynolds number (Viscosity)?

2. If you have a linear range that is a combination of changing flowrate and viscosity this becomes even harder to deal with:
   I. Have to linearise with Reynolds number somehow, but how?
   II. How often do we calibrate, the API definition should be based on Reynolds number not just viscosity!

3. If the meter is properly calibrated and linearized for Reynolds number then:
   I. If that linearsation is good, and the method holds up under operation, then proving will be straight forward.
      1. Note however if you use traditional proving flowrate linearising methods to "improve the calibration on site, the meter will still need to be corrected for Reynolds number not flow rate.
   II. If, as can easily be the case, the linearisation method does not work well, then we are back to a more disconcerting case 2, but with the added complexity of uncovering the effects of linearization.

Two examples that come easily to mind are the case of USMs operating at low Reynolds numbers at startup [2]. In this case the meters had to be essentially re-linearised on site, a costly and time consuming exercise. Another example is the case of a USM operating in the non-linear range with a poor determination of viscosity. This meant the corrections were being applied at the wrong Reynolds numbers, figure 6. It was located in the North east of the US. The nominal viscosity was 4cS, but through the year the viscosity changed, as it was supplied from storage tanks, from 1.5-6cS, a Reynolds number variation at a constant flow of 4:1. The user was disconcerted to see his proves varied through the year at "constant flown rate" by as much as 0.4%. His turbines he replaced changed by 0.2%, he was expecting to do better with the USM.

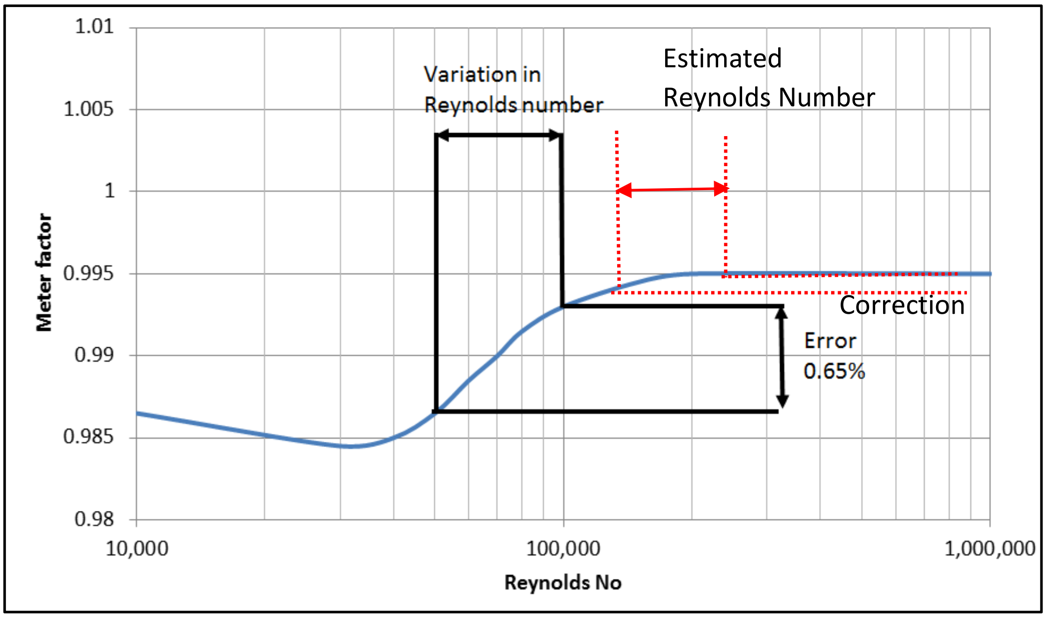


Figure 6 - Mis-Linearisation of a USM

5 EXTRAPOLATION

If we accept that the meter is basically non-linear and needs to be corrected, we then must accept that we need to know the shape of the curve that is to be linearized. The basic method to do this is by calibrating the meter. If the non-linearity is a function of Reynolds number then we must accept that we need to know the shape of the calibration curve across the operational Reynolds number range. Here we walk into the issue of what uncertainty do we require, and how big is the correction. To ensure the best uncertainty it is essential that the meter be characterized over the full operational range of Reynolds numbers, but what happens if we do not. If for example we chose to calibrate an 8" meter to operate on 40cS oil with water. The bottom Reynolds number on water will be around 170,000 and the top Reynolds number for oil will be 56,000. The Calibrations do not even overlap. So any non- linearity in the curve will not be caught by the water calibration. An **uneducated extrapolation** of a 4" meter is shown in figure 7, the potential difference in calibration curves can be clearly seen.

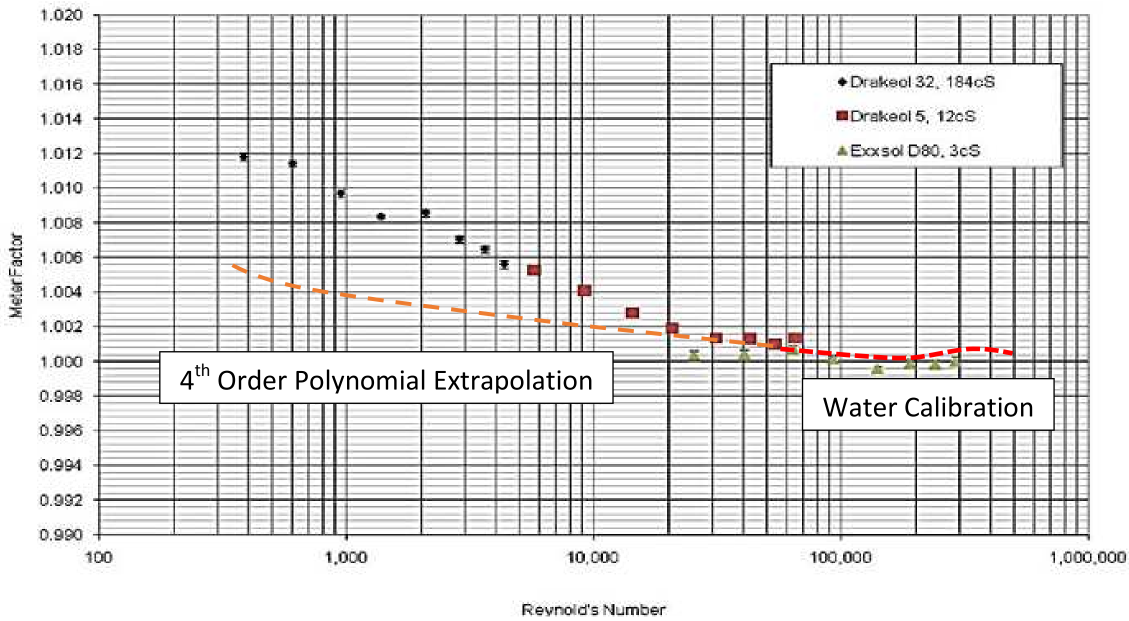
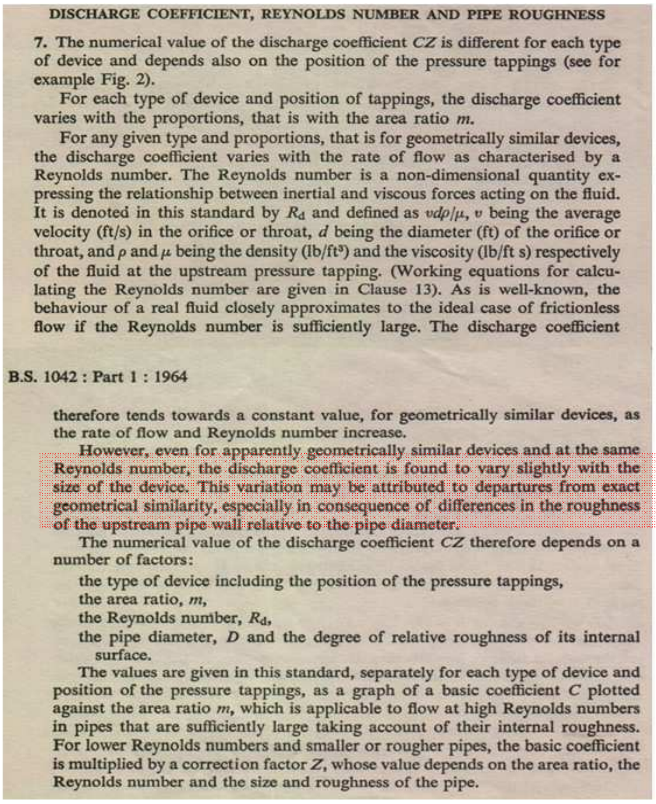


Figure 7 - Calibration of a 4" Coriolis Meter

It may be said that this is an uneducated extrapolation and we know the shape of the calibration of our meter. This would be for example the principle used for using an orifice plate without calibration, using ISO 5167. However, the uncertainty level is not 0.1%. It must be recognized that there is an extra uncertainty that must be included for the extrapolation. The viability of such extrapolations depends on the meter type, the manufacturing processes and the backlog of collected data. It therefore takes a long time and is a costly process to produce sufficient proof of the veracity of such a method. As far back as 1964 in the BS1042 standard for orifice plates the authors clearly recognized the fact that meter reproducibility was a problem in determining the effect of Reynolds number, figure 8.



DISCHARGE COEFFICIENT, REYNOLDS NUMBER AND PIPE ROUGHNESS

7. The numerical value of the discharge coefficient CZ is different for each type of device and depends also on the position of the pressure tappings (see for example Fig. 2).

For each type of device and position of tappings, the discharge coefficient varies with the proportions, that is with the area ratio m.

For any given type and proportions, that is for geometrically similar devices, the discharge coefficient varies with the rate of flow as characterised by a Reynolds number. The Reynolds number is a non-dimensional quantity expressing the relationship between inertial and viscous forces acting on the fluid. It is denoted in this standard by R_d and defined as $vd\rho/\mu$, v being the average velocity (ft/s) in the orifice or throat, d being the diameter (ft) of the orifice or throat, and ρ and μ being the density (lb/ft^3) and the viscosity (lb/ft s) respectively of the fluid at the upstream pressure tapping. (Working equations for calculating the Reynolds number are given in Clause 13). As is well-known, the behaviour of a real fluid closely approximates to the ideal case of frictionless flow if the Reynolds number is sufficiently large. The discharge coefficient

B.S. 1042 : Part 1 : 1964

therefore tends towards a constant value, for geometrically similar devices, as the rate of flow and Reynolds number increase.

However, even for apparently geometrically similar devices and at the same Reynolds number, the discharge coefficient is found to vary slightly with the size of the device. This variation may be attributed to departures from exact geometrical similarity, especially in consequence of differences in the roughness of the upstream pipe wall relative to the pipe diameter.

The numerical value of the discharge coefficient CZ therefore depends on a number of factors:

the type of device including the position of the pressure tappings,
the area ratio, m,
the Reynolds number, R_d,
the pipe diameter, D and the degree of relative roughness of its internal surface.

The values are given in this standard, separately for each type of device and position of the pressure tappings, as a graph of a basic coefficient C plotted against the area ratio m, which is applicable to flow at high Reynolds numbers in pipes that are sufficiently large taking account of their internal roughness. For lower Reynolds numbers and smaller or rougher pipes, the basic coefficient is multiplied by a correction factor Z, whose value depends on the area ratio, the Reynolds number and the size and roughness of the pipe.

Figure 8 - BS1042 Statement on Reynolds Number Correction

We have concentrated on extrapolation in the downwards direction of Reynolds number, but also it should be pointed out the same is true for upward extrapolation. We have said that in general the higher the Reynolds number the more stable to operation of fluid mechanics. This is not always the case and such an assumption can be fraught. In the past such orifice plates as the conical entry plate were designed to have a good low Reynolds number performance. It was assumed that once a good linear meter had been produced it would continue to high Reynolds numbers. In fact there is a 1% change in the calibration at high Reynolds numbers due to the change in surface boundary layer from laminar to turbulent. A similar issue was shown in figure 2, with vortex shedding. Thus the current propensity for assuming that a meter calibrated on water will operate in the same way for LNG at much higher Reynolds numbers may not be true!
To summarize, the assumption that has to be made is, the extrapolated data follows the curve of the meter at the end of calibration. Often the assumption is that the meter is now completely linear, a feature of many Reynolds number based meters as they increase in Reynolds number. The problem comes if there is an unexpected discontinuity in the calibration. This of course will never be known until tests can be carried out at the extrapolated flowrates, or the meter shows differences to the expected performance, by for example a mas balance of the system. If this method has to be used then it is imperative that supplier shows:

- The method in detail.
- The data to back up the extrapolation.
- And importantly an independent assessment of the extrapolation method and how strong it will be in the application.

The uncertainty for extrapolated meters will always be greater than for a meter calibrated over the operational range.

6 CALIBRATION

It is hopefully clear now that meters with Reynolds number non-linearity in applications where we are looking for low uncertainty need to be calibrated, as far as possible over the operational range. At present there is no good independent proof to tell us that any of the meters can be calibrated by "assumption". This unfortunately requires the user to pay more money because calibrating liquid meters over a wide Reynolds number range is not inexpensive, water is much easier and cheaper. These meters are, however, the only source available to measure the dollars passing through a flow line, particularly hydrocarbon. Without the proper calibration, even with proving there is always a risk the calibration will change with time. This drops down to dollars moving in an unknown direction (The definition of uncertainty). At least with the correct calibration, it is possible to understand where the meter is starting from and to determine the attention that needs to be made to the operation and linearization of the meter.

The quality of calibration is also an issue. Poor calibration can be as damaging as no calibration. Initially of course calibrations should be carried out at facilities that are independently audited to an international standard. This does not necessarily require that it be an independent facility, although that may add credibility. The methods and requirements at least have a standard in AGA, particularly for Gas USMs, although as previously stated this leaves much to be desired. The concept of only producing 2 or 3 "as left" points is odd to say the least. In fact in some recent liquid calibrations of USMs using the same principle, it was clear that points could be chosen that appeared to make the curve much better than it actually was. For liquid measurement there is very little current discussion in standards as to the method of calibration and its requirements. This leaves it in the hands of the manufacturer and possibly the calibration facility if independent. While a calibration facility can give advice, in general its purpose is to do the calibration in line with the customers (often the manufacturer) order.

7 CONCLUSIONS

- Reynolds number must be acknowledged as a major factor in the performance of flow meters.
- All meters are subject to non-linearity due to Reynolds number and generally have to be corrected.
- This correction should be more transparent to the user.
- When extrapolation is used it will always increase the measurement uncertainty.
- This can be alleviated by the correct calibration of the meters.

8 REFERENCES

[1] Cousins T. "HOW SAFE IS LINEARISATION OF FLOW METERS?" ISSFM 2011

[2] Cousins T. "Is Linearisation Safe for Custody Transfer?" NSFMWS 2014

[3] BS 1042: Part 1:1964

[4] T. Cousins "VISCOSITY AND ITS APPLICATION IN LIQUID HYDROCARBON MEASUREMENT" ISHM CLASS 2O13.

[5] T. Cousins "The Reynolds Number Correction of Liquid Ultrasonic Meters and Coriolis Meters" CEESI/VSL Conference 2014 Lisbon.

[6] Liptak B.G - Editor in Chief "Instrument-Engineers-Handbook-Fourth-Edition-Volume-One-Process-Measurement-and-Analysis" Fourth edition CRC publication for ISA

[7] Baker R.C "Flow-Measurement-Handbook" Cambridge University Press.

[8] Augenstein D. & Cousins T. "Validating the Accuracy of Multi-Path Transit Time Ultrasonic Flowmeters" ISSFM, Alaska, 2010

[9] Cousins T. "EFFECT OF SWIRL ON 8 PATH METERS" CEESI Workshop Singapore 2010.

[1-] Augenstein D & Cousins T. "THE PERFORMANCE OF A TWO PLANE MULTI-PATH ULTRASONIC FLOWMETER" Northsea Flow Measurement Workshop, 2010.

[11] Brown G, Estrada H, Augenstein D, Cousins T, "LNG Allocation Metering Using 8-Path Ultrasonic Meters" Northsea Flow Measurement Workshop, 2007

[12] Brown G, Augenstein D, Cousins T. " The relative Merits of Ultrasonic Meters Employing Two to Eight Paths", SEAWS, 2006.

[13] Liptak B.G - Editor in Chief "Instrument-Engineers-Handbook-Fourth-Edition-Volume-One-Process-Measurement-and-Analysis" Fourth edition CRC publication for ISA

[14] Baker R.C "Flow-Measurement-Handbook" Cambridge University Press.

[15] Augenstein D. & Cousins T. "Validating the Accuracy of Multi-Path Transit Time Ultrasonic Flowmeters" ISSFM, Alaska, 2010

[16] Cousins T. "EFFECT OF SWIRL ON 8 PATH METERS" CEESI Workshop Singapore 2010.

[17] Augenstein D & Cousins T. "THE PERFORMANCE OF A TWO PLANE MULTI-PATH ULTRASONIC FLOWMETER" Northsea Flow Measurement Workshop, 2010.

[18] Brown G, Estrada H, Augenstein D, Cousins T, "LNG Allocation Metering Using 8-Path Ultrasonic Meters" Northsea Flow Measurement Workshop, 2007

[19] Brown G, Augenstein D, Cousins T. " The relative Merits of Ultrasonic Meters Employing Two to Eight Paths", SEAWS, 2006.