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Turbine Meters in Decline - Throwing the Baby Out with the Bathwater

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ABSTRACT

While there is no doubt that the new meters, Coriolis and USMs, have some great advantages, the fact that no single flowmeter is best for all applications is being lost in the almost born again Apple like fervor to promote them. This results in missing the true advantages of older meter designs such as the turbine meter.

The paper describes the design and operation of turbine meters, concentrating, unlike past papers, on the methods used for linearizing them by modifying the basic physics by changing the rotor aerodynamics. Thus unlike the Coriolis and USM their base performance does not require a base viscosity to be determined to correct them. Once linearised they find their own Reynolds number correction by virtue of the fluid dynamics.

The paper presents large amounts of data showing the effect and methods of linearisation, the Reynolds number performance of turbine meters and discusses some of the installation effects

1 INTRODUCTION

"We humans have a talent for deceiving ourselves. Skepticism must be a component of the explorer's toolkit, or we will lose our way. There are wonders enough out there without us inventing any" Carl Sagan.

We see this continuously now in the area of flow measurement, the new is automatically better in every way compared to the old. The result is that we throw away or dismiss experience, quality and competent meters. Further we are prepared to bend practices that have served well to make the new meters acceptable. Is this the whining of an old man, for whom technology has passed him by? Unfortunately this old man loves the new technology, Ultrasonic flow meters have provided him the most interesting years in flow measurement, but this should not obscure their faults, **the talent for deceiving ourselves**, and we should be aware that there is no one flowmeter that solves every flow problem. The variations in required performance, the fluid conditions, the ambient conditions, the flowrates etc. all make it fundamentally impossible for one technology to solve every measurement problem, even though marketing would have it so.

This brings us therefore to the subject of the paper, turbine meters. When I first worked in flow measurement they were the de-facto standard for measuring low uncertainty fluids. They had their faults, and of course we used them for measurement applications where they were inappropriate, and like all meters they had at times reliability problems. However, within the grand scheme of things they produced generally good results, which even in hindsight still stand. However, talk to most new young engineers and technicians and if they even consider them they are immediately dismissed, old technology, moving parts, totally unreliable and so Coriolis and USMs are taking over rapidly within such an environment.

With the development of the new CEESI oil calibration facility my first reaction was to use USMs for master meters. My experience had however counselled me to look around, I knew that I would have problems with proving them, in fact I knew that I would need to use a master meter system to calibrate USMs successfully. So I decided to look again after many years away at turbine meters, and realized that I was probably also guilty of deceiving myself! This has made me look again at turbine meters and to realize that they still have a place in low uncertainty flow measurement.

The paper sets out to at least give an insight for those new to turbines, and for those who have forgotten about them jolt their memories about the qualities they possess and hopefully give a balanced assessment as to their value in the flow measurement world.

2 METHOD OF OPERATION

The paper is not intended to have a detailed discussion of the design, there are plenty of references for this, but to point out the salient features so that the data and calibrations can be explained. The turbine meter is simply a set of blades set at an angle to the fluid mounted around a hub on an axle, figure 1.

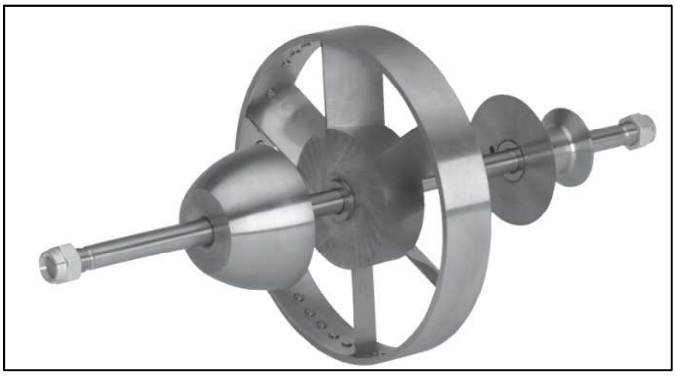

Figure 1 Turbine Meter Rotor Assembly

The fluid across the blades produces a lift force which, because the axle constrains the movement to an axial motion, causes the assembly to rotate. This imparts an angular velocity (RPM) to the turbine rotor which is proportional under ideal conditions to the linear velocity of the fluid.

Many turbine meters use a set of blades set at an angle to the oncoming flow to produce lift, figure 2.

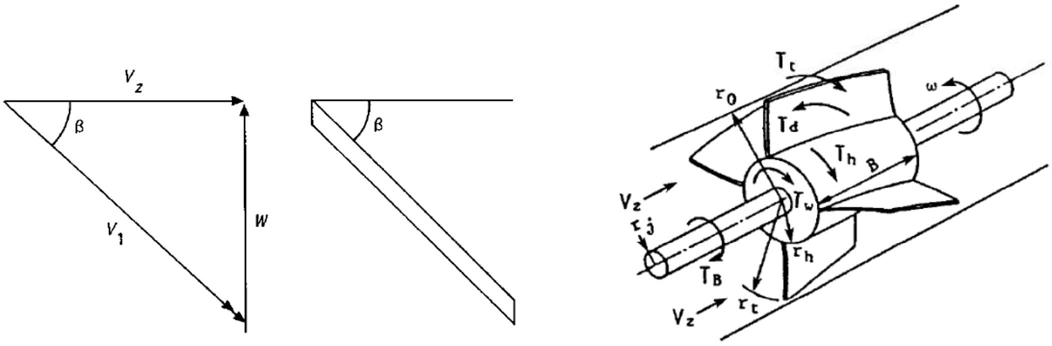

Figure 2 Forces and Flow on a Turbine Meter Rotor [1]

Under ideal conditions these will cut through the fluid to form a perfect helix. Using this basic concept the value of the oncoming flow velocity can be obtained by determining the frequency, f, of the blades passing a fixed position.

$$V_z = w/\tan\beta \quad \text{……………………} [1]$$

And

$$f = N\tan\beta V/2\pi r \quad \text{…………………}[2]$$

Where N is the number of blades, β the blade angle, V the oncoming fluid velocity and r the point of measurement along the blades.

The rotor accelerates until the driving torque on the blades balances the sum of the resisting torques. The resisting torques are the hydraulic drag of blades, bearing friction, both from the axial and the end thrust bearings and viscosity. For the steady state condition the following relationship is obtained for the torque produced by the lift and the various drag components:

$$T_d = T_B + T_t + T_w + T_h \quad \text{………} [3]$$

Where: T_d is the torque produced by lift on the blades, which by virtue of being a lift component is Reynolds number sensitive.
T_B is due to the rotational bearing friction
T_w is due to the end thrust bearing friction, sometimes alleviated by floating rotor designs.

T_t is the tip blade clearance drag, which can have a significant impact on the shape of the calibration curve, and the Reynolds number performance.
T_h is the fluid dynamic drag on the rotor, which again because it is a function of the drag will be Reynolds number sensitive.

When the meter is running at the point where the meter is linear it is assumed that the bearing and tip blade drags are so small compared to the lift and fluid dynamic drags that they are zero. At this point the equation becomes:

$$T_h = T_d \quad \text{……..}[4]$$
$$T_h - T_d = 0 \quad \text{……..}[6]$$

There are a number of different equations for torques[1], but essentially they end up with an equation similar to:

$$\int_{r_h}^{r_t} \frac{r V_z^2 c}{\cos\beta_m}(KC_L - C'_D \tan\beta_m)dr = 0 \qquad \text{……………}[7]$$

Where r_t and r_h are the radius at the hub and tip of the blades respectively. C_L and C'_D are the corresponding lift and drag coefficients for the blades. K is the correction from a single blade to a cascade and c is blade width.

Equations in themselves are interesting but they do also hopefully tell us the potential issues we will see in using the meter. The above tell us:

- Bearing friction is going to be an issue if the fluid forces are not sufficient to overcome them. Further if they are a big contribution then as the bearings change their characteristics the calibration is likely to change.

    - Lesson: do not use the meter at low flows where the bearings will affect the performance.

- It tells us the performance will be subject to tip blade clearance.
    - Lessons: The design will be influence the performance, a shroud for example will have a significant effect. Also it tells us the Reynolds number will play a part. Also any build up on the walls or shroud will affect the performance.[2]

- Equation 7 shows that variation in velocity profile along the blades will change the calibration.
    - Lesson: upstream flow profile is likely to affect the performance.

- Equation 7 includes a lift and drag coefficient.
    - Lessons: both are well known to be sensitive to Reynolds number, further the shape of the blades will influence the meter performance.

2.1 Performance

The performance of the turbine meter is encapsulated in several issues:

- Reynolds Number
- Calibration.
- Design, particularly the blade design.
- Installation and Proving.

The paper does not discuss pick up design etc. reference [1], describes the operation. It should be noted that some inductive pickups do give a drag to the rotor, but this is generally only an issue on very small meters.

The classic curve shown in most literature for a turbine meter is shown in figure 3. At the lowest flown there is no rotation as bearing friction is too great compared to the lift available. Finally the lift is sufficient to turn the rotor, but going to equation 3 it still provides a large retarding force. During this section the rotation is not directly proportional to the flow velocity. Classically there is then a hump as the meter becomes linear. This is largely controlled by the tip blade clearance. Finally the meter reaches the point where there is a solid linear relationship between velocity and rotation. It is generally accepted that the sweet spot for the turbine is to operate at around 75% of the rated full scale flow.

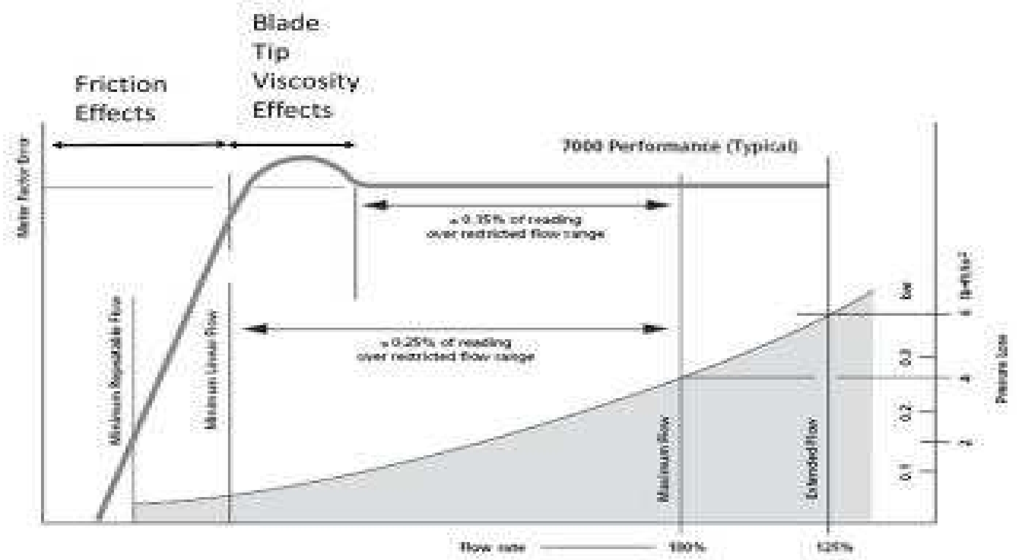

Figure 3 Classical Turbine Calibration Curve [1]

This curve would be typical for a low viscosity fluid such as water.

2.2 Reynolds Number

Unfortunately, as with all meters, we come back to Reynolds number. Turbine meters when away from the effect of bearing friction are subject to Reynolds number. The classical set of curves for a flat bladed meter are shown in figure 4. When plotted against Reynolds number it can be seen that away from the bearing friction effects there is a good agreement of the curve with Reynolds number.

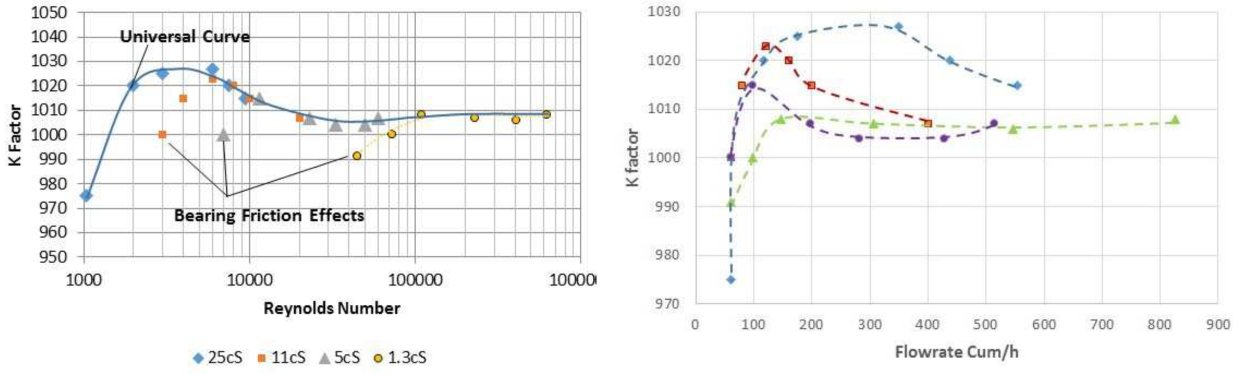

Figure 4 Calibration of a Flat Bladed Turbine Meter [2]

It can be seen clearly that the flat bladed meter suffers from changing calibration with a relatively small change in viscosity, evidenced by the hump produced at low Reynolds numbers. It should be noted however the effect varies significantly with meter size, the larger the meter the less the effect. Blade configuration effects the performance, as we will see with helical blades have a more stable performance with Reynolds number than than flat blades. Tip blade clearance and mechanical design will affect the performance.

2.3 Calibration

To an extent the meter linearity can be improved for a given viscosity, Reynolds number, by modifying the blades. Very few ouside of the manufacturers understand how turbine meters are linearised. The meter is calibrated intially and a calibration curve ascertained. Once this curve is determined a technicnician will either file nor bend the blades to make the calibration curve the required shape. The usual practice is to perform a calibration using the calibration fluid. If this curve is not within the specification of the meter, it is removed and the blades modified. Figure 5 shows a set of experimental data[1] for the effect of changing the downstream of a flat bladed turbine meter. A similar set of curves can be obtained for the upstream of the blades. In practice the most common method of modification is to use a file on the blades, usually done by a technician "who knows how to do these things!!" There is generally not a procedure that specifies in detail how exactly to modify the blades.

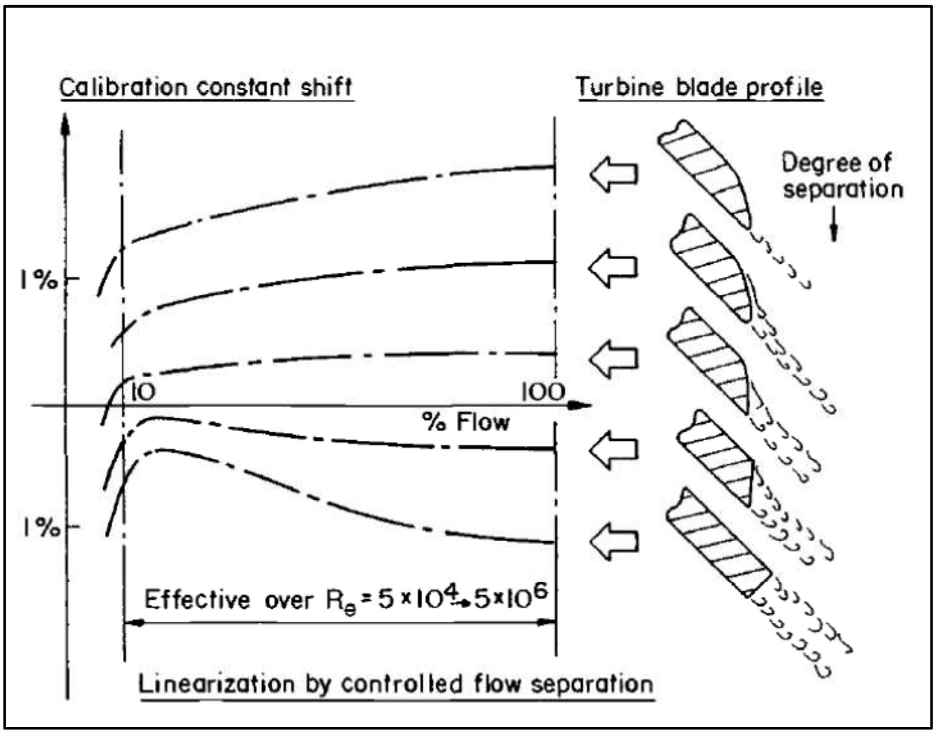

Figure 5 Effect of Blade Modification on the Calibration [1]

The effect of modifying a production 6" turbine is shown in figure 6 [3]. The meter is shifted in terms of K factor and it is linearized.

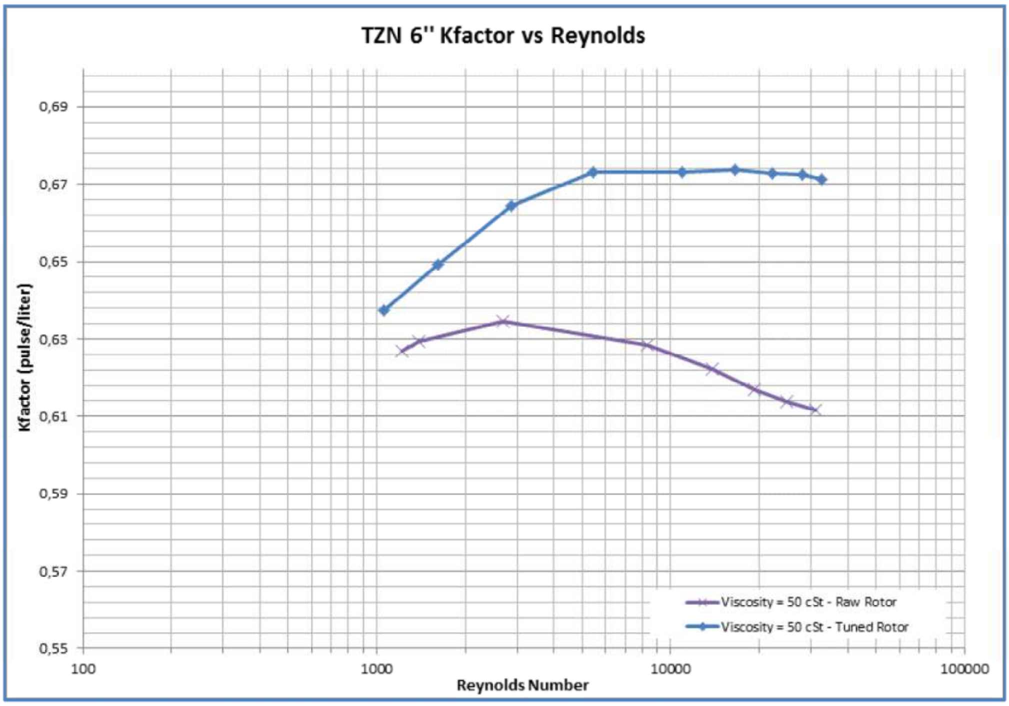

Figure 6 Modification of Meter Calibration

The essential points to make about this method are:

- It implies that unless the meter is calibrated over the range of operation, in terms of Reynold number the meter will be non-linear when in operation.
- The method of linearization, unlike that for Coriolis and USMs is by modification of the physics of the meter, rather than by software correction. This implies that the meter essentially when modified for a given Reynolds number will be self-correcting, and does not require the exact knowledge of the fluid viscosity. The only way in which the meter will differ on site from the calibration will be due to installation effects.

2.4 Design, Blade Configuration

The major difference in designs revolves around the blade configuration. The "standard" design is based on flat blades forming the rotor. This is simple and robust to construct. Fluid dynamically it does give issues as the flow "separates" across the blades resulting in it being very susceptible to Reynolds number variations, figure 7. To improve this performance the helical bladed meter was developed, figure 7. The design is such that across the rotor the boundary layer of the fluid does not separate, resulting in a more consistent operation with Reynolds number. This does not mean that without modification the meter is linear. It still has to be modified in a similar way to the flat bladed meter, it is just that the modification is less and the consistency over the range is better.

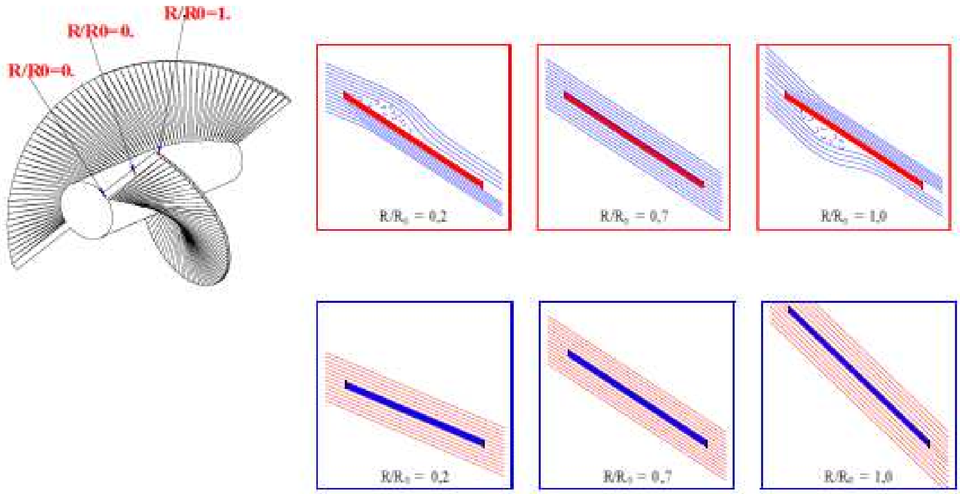

Figure 7 Flow Across a Flat and Helical Bladed Rotor [2]

Figure 8 shows an 8" helical bladed meter that has been modified over a 2000:1 Reynolds number range. Over 230:1 the linearity is +/- 0.3%. The dotted line is the shape of the curve before modification.

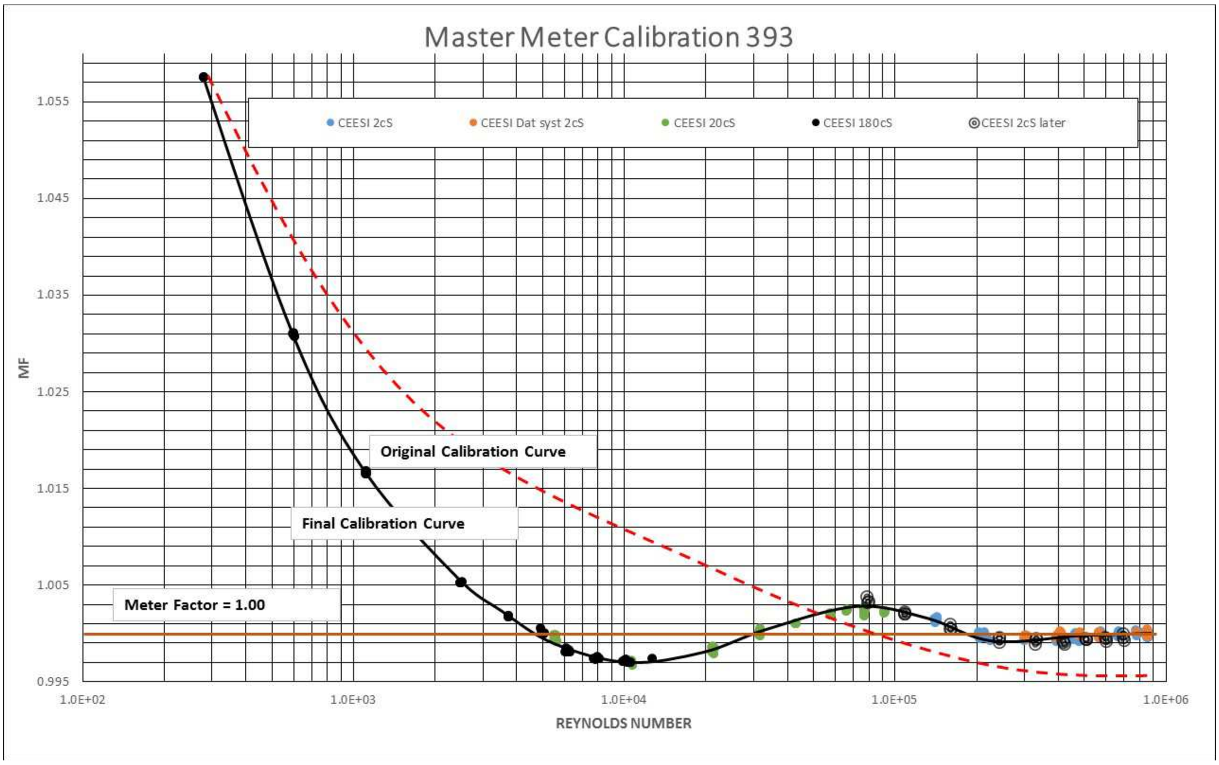

Figure 8 Calibration of an 8" Helical Bladed Turbine Meter

It should be noted that this meter was modified over such a large range for the CEESI calibration facility, two other meters have very similar curves. Normally the meter would be “corrected” over a smaller range and would have a much tighter linearity.

2.5 Installation and Proving

One of the major criticisms of turbine meters is their susceptibility to flow induced installation effects, such as profile distortion and swirl. There is no doubt that the meter is particularly prone to calibration change due to swirl, and that generally speaking they should be protected by some form of flow conditioner. The de-facto standard is the tube bundle, not the world’s greatest and most consistent conditioner, but generally good at reducing the effect of swirl. Certainly it would not be sensible to install a turbine meter in operation without a conditioner and expect a good installed uncertainty without proving. Equally they may not be as bad as the conventional wisdom predicts. Figure 9 shows the calibration of an 8” Helical meter installed at CEESI compared to the manufacturer’s calibration. The Manufacturer used a CPA flow conditioner, the meter at CEESI, had no conditioner and is 10 diameters downstream of a large header. Over the range, where the meter is not affected by bearing drag, the two agree within 0.03%. The combined uncertainty of the two facilities is 0.08%, excluding the uncertainty of the meter. The same effect was seen with the other two meters.

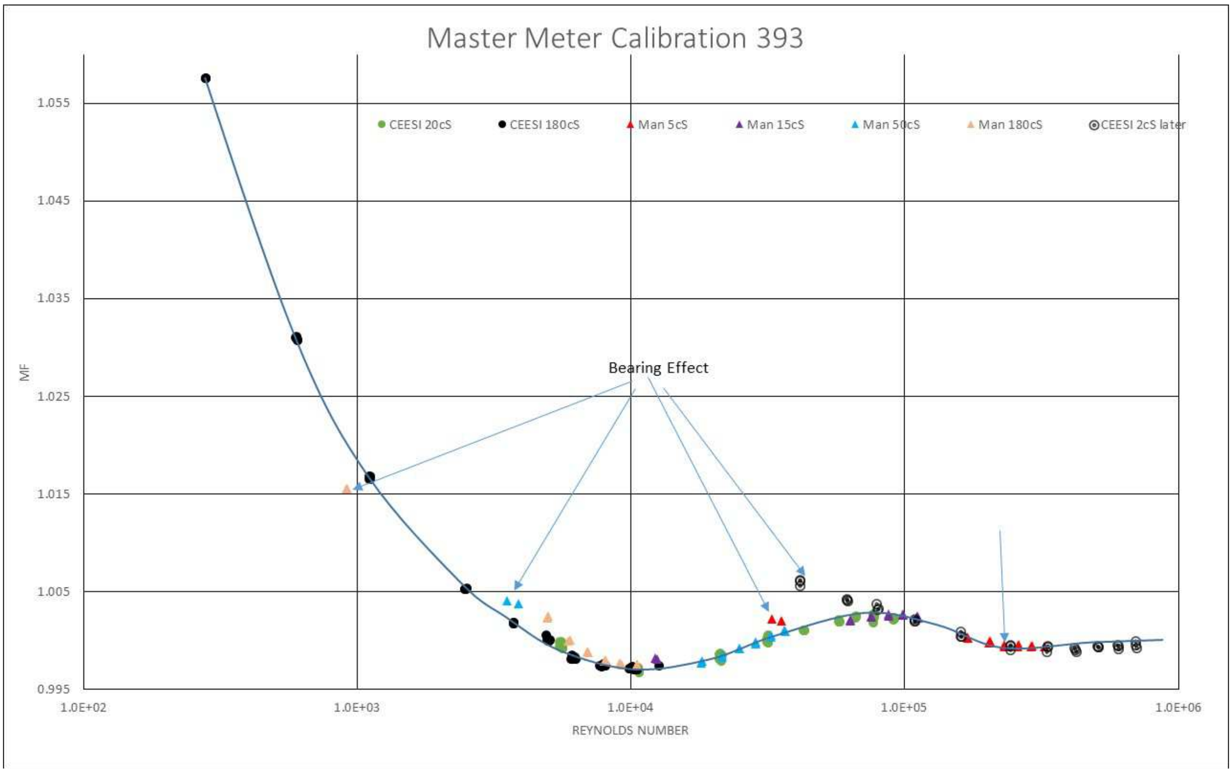

Figure 9 Comparison of CEESI Calibration with Manufacturer

This should not however be taken as an absolute that this will happen, there is plenty of data to show that the calibration can shift with installation, and it is better to safe than sorry and use a flow conditioner.

Equally for the best performance a prover should be used, in the end it removes the concerns with installation, and when we are looking for 0.1% then that confidence is needed with flow measurement.

It is with proving that the turbine truly comes into its own, because essentially the prover was designed for turbine meters, and as such is at its most effective. Much has been said of the lack of diagnostics available for turbines when compared to Coriolis and USMs, but the prover is truly effective as a diagnostic for a turbine meter. It is not just the variation in the prove meter or K factor that tells the tale, it is the general rule of repeatability of turbine meters. If the repeatability of the turbine meter is worse than 0.05% in 5 runs then something is wrong. There could be a flow problem, the meter could be failing, there could be leaks, or the prover could have issues. The point is that if it does not meet this criteria there is almost certainly a problem. With the Coriolis and USM, if proving does not meet this criteria or any consistent criteria of repeating it probably means that the meter is just not proving well [4], it does not necessarily mean there is a problem.

3 RELIABILITY

Perhaps the biggest complaint against the turbine is the fact that it has bearings, and hence moving parts. The result is thus failure over time by bearings wearing out and also being prone to failure due to bearings becoming blocked. There is a truth in both of these views, but equally the long term reliability issue can be addressed by the right application. It is obvious that the meter should not be used where the fluid has poor lubricity, this will certainly reduce the life of the meter and result in the early demise of bearings. It should be noted that Gas turbine meters have a lubricant injected into the bearings, this is not feasible on liquids. Any fluid, particularly cleaning fluids that attack the bearing material, generally tungsten carbide for liquid meters will reduce the life expectancy. A common cause of damage is over speeding, many times I have come across meters that have been “steam cleaned”, subjecting the meter to a quick burst of high pressure, high velocity steam. A combination of temperature and velocity will be sufficient to ensure internals of the meter will be found downstream of the meter section. Under good conditions however the expectation of meter life can be several decades. In 2000 I audited turbine meters measuring crude coming from the gulf of Arabia to Alexandra in Egypt. At the time these had been in operation for nearly 30 years, with only two of the 25 meters having any repair over that period of time. Their calibrations did not change outside of the uncertainty limits, and to my knowledge they are still in operation.

The buildup of material in the bearings is not as straight forward. There should always be some filter or strainer upstream to protect the meter, but this is also true of all meters with the possibility of buildup. Both USMs and Coriolis will have their performance affected with the buildup of material, USMs are likely to get it in the ports and Coriolis will see a calibration shift with buildup of material trapped in the tubes. Perhaps the big difference is that the Turbine is likely to stop working! A nuisance but at least it makes one think about the issue. Having a meter operate but giving the wrong answer is not a great solution. Wax buildup is a typical issue, times there are complaints that a turbine will stop working with wax in the meter. The fact is there should be no measurement using any meter with wax build up, the problem needs to be resolved.

4 DRIFT

One area that is difficult to understand and quantify is the long and medium term drift of a turbine meter. In the US it is generally accepted that the proving reproducibility should keep the meter within 0.2-0.25%. This comes largely from the history with turbine meters. A control chart of a turbine meter will often show that the proves drift over time to this span. The reasons for this are not clear, but possibly it is the mechanical movement that causes the meter to locate into different positions.

5 MIXTURES

Like all single phase meters they have issues with multi-phase flow measurement. Turbine meters seem to work in the same way as all meters with water in oil mixtures. As can be seen from the calibration shown in figure 10 [5], above the point where the water and oil mix then the meter does a good job of measuring the combined water and oil volume, the data is not clear as to whether they retain the same level of uncertainty, but there is good agreement. Once the water separates out at the lower velocities the meter uncertainty increases significantly.

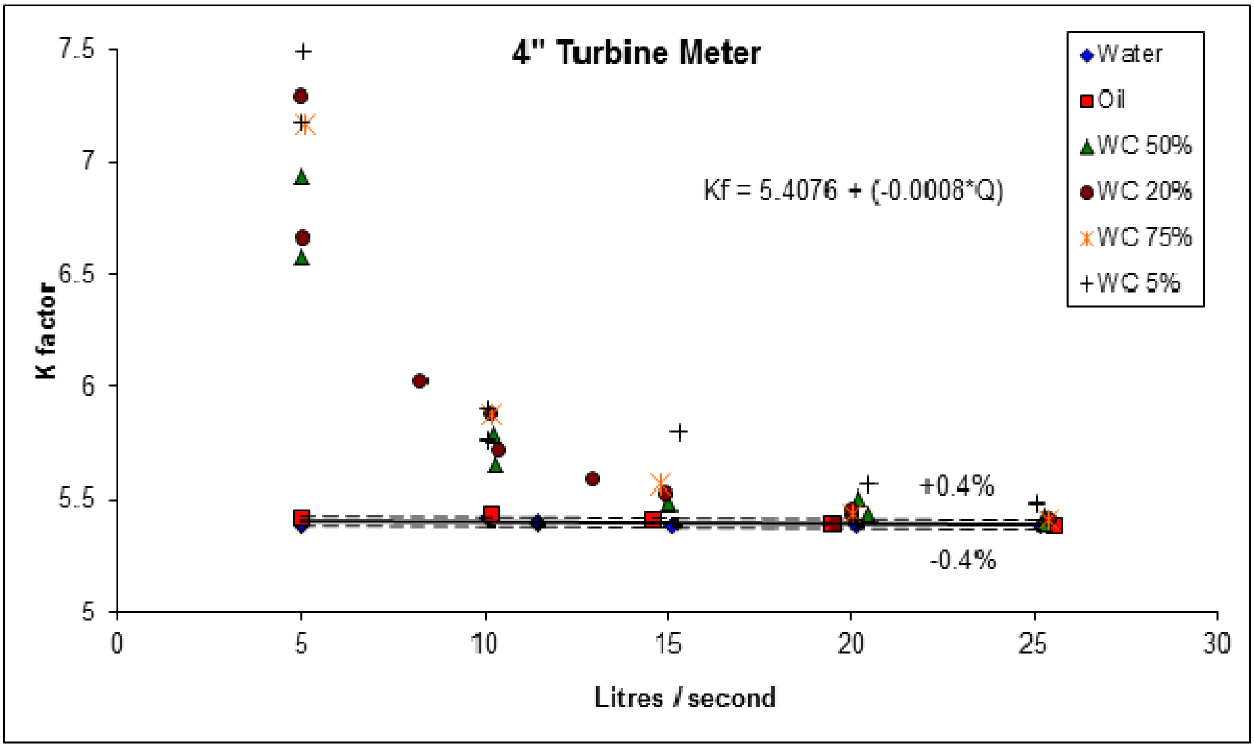

Figure 10 Calibration of a Turbine Meter with High water Oil Mixing

"Fiscal measurement of oil with high water fraction" [6] gives a very good account of the issues relating to measurement of oil in water mixtures, including the effect on such issues as the corrections Ctl etc.

Less data is available on the performance of a turbine meter measuring a gas in oil mixture. The only circumstantial evidence I have, comes from the replacement of turbines by USMs in a leak detection system. Unfortunately gas would be mixed in the oil towards the end of each tank in the application. The customer was disappointed that the USM would essentially stop reading because of the gas interference with the signals, or became very noisy, when his old turbines kept running. This would result in leak detection alarms from the USM system. However, what answer was given by the turbines is a matter of conjecture. Again it would be expected that if fluids mixed the turbine would measure the combined volume.

6 CRYOGENIC METER

With the metering world looking at measuring LNG, interest in cryogenic metering is increasing. This is concentrated on Coriolis and USMs, and we have forgotten the turbine meter. They have however been used successfully in this application for many years. Figure 11 shows the calibration of a 2” IDEX turbine meter on water and the NIST liquid nitrogen facility, now in operation at CEESI. Against Reynolds number it can be seen that the curves are joining together at the high end of the water and low end of the liquid nitrogen curves. There is a shift between the two calibrations but the actual scatter of the low end results on the liquid nitrogen includes the water calibration.

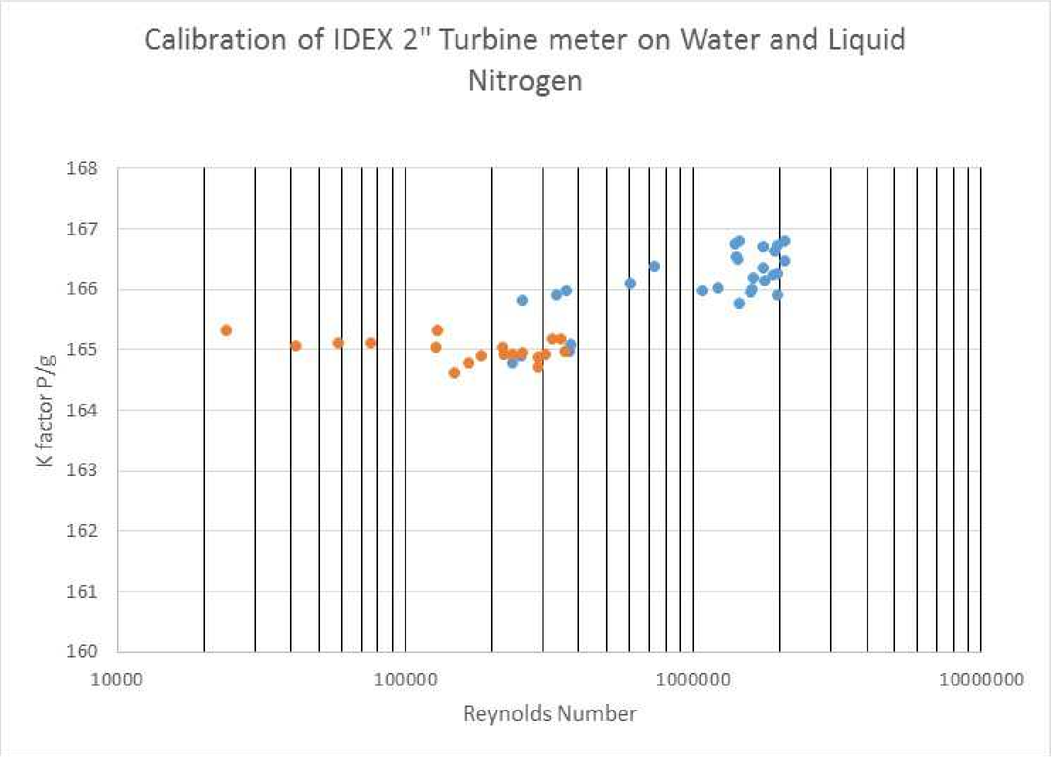

Figure 11 Calibration of 2" Turbine Meter on Water and Liquid Nitrogen

7 CONCLUSIONS

The paper put forward the concept that with turbine meters we should not "throw the baby out with the bathwater" because it is old technology. That the meter still has some very good attributes and that when looking at flow meter applications it should always be considered. The paper went through the theory and some of the operational aspects to explain again the possible value and also the downsides of the meter. From it the following conclusions can be drawn:

- Under good flow conditions, lower viscosities, say below 50-100cS the performance can be as good as any meter.
- The repeatability, particularly in combination with a prover is probably better than any other meter, and gives the opportunity to use the prover as a method not only of calibration but a diagnostic tool.
- The method of linearization is very strong compared to other meters, especially if calibrated correctly under similar conditions to the operation.
- They are probably as good as other single phase meters at dealing with water and gas in oil.
- They have a good history with cryogenic operation.
- Care must be taken to avoid build up in the meter and contamination of the bearings.
- There is an issue with long term stability in some meters.
- Care must be taken with installation, and it is advisable to include a flow conditioner.

Overall the meter should still take its place in consideration when reviewing meters particularly for use in Fiscal/Custody transfer of clean hydrocarbon liquids.

So to end with an appropriate quote by the physicist Richard P Feynman that can be applied to reviewing the use of flow meters **"**For a successful technology, reality must take precedence over public relations, for nature cannot be fooled."

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