Turbine flowmeter and viscosity effects of liquid hydrocarbons

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Abstract

The article presents the results of tests carried out in turbine meters to investigate the effects of different viscosities in the curves, and to explore mathematical ways to express the low flow rate part of the curves in order to use them as a functional part of the flow meter curve, with some loss of uncertainty, but even so useful in a number of cases. The turbine meters have diameters of 25 mm, 40 mm and 50 mm, and the tests were carried out with three different viscosities of fluids (7cSt, 17cSt and 34cSt).

The results have shown that two of the mathematical curves used to adjust data gave results that were good enough to improve dramatically the range of operation of the tested turbines, without losing quality. The 25 mm may have a rage of operation of 1:1200 (uncertainty degrading to 0,8% to 0,9%), the 40 mm a range of 1:340 (0,2% to 0,3%) and the 50 mm a range of 1:150 (0,6% to 1,1%).

This approach may open possibilities to simplify the use of multiple viscosities operations with the same calibration curve in a large range of flow rate.

Introduction

Turbine meters are some of the most common and accurate type of flowmeters used to measure expensive fluids, be it gas or liquid, in the industry. In spite of their excellent repeatability and accuracy, it is well known that the results of the flowrate measured with turbine meters are highly dependent on the viscosity of the fluid, especially for liquids, and in not so large diameters.

A relatively small number of studies were published in the last fifty years on the dependence of the error curves of turbine meters on the viscosity, but there is still an open field for studies of better mathematical models to a controlled use of the nonlinear part of the curve that would allow an enlargement of the range of operation, in spite of the degradation of the uncertainty level to some extent.

The behaviour of the calibration of three turbine meters (diameters of 25 mm, 40 mm and 50 mm) was studied as a function of three different viscosities (7 cSt, 17 cSt and 34 cSt). Two mathematical models for the curves were tested and presented in the paper, for three different coordinated pairs of dimensionless numbers.

The reasons to this study include

a) to investigate the possibilities to enhance the range of operation of turbines in a controlled way (with some deterioration of the uncertainty but even so in a controlled way);
b) the use of the nonlinear part of the curves;
c) to produce quality information to allow the use of a turbine meter with a different viscosity from that of the calibration, within certain limits, which is a situation that occurs quite often in the petroleum industry;
d) to help in this effort there are the proposition of appropriate mathematical functions to describe the experimental data, aiming to have an improvement of the understanding of the error curve of a turbine;
e) to investigate if there were possibilities to calibrate turbines with perhaps two fluids of very different viscosities and find a very good curve describing the uncertainty and error curve for the viscosities in between.

Review

Hochreiter (1958) was perhaps the first to make a study correlating dimensional analysis of the turbine flowmeter, arriving to a dimensionless numbers very useful to relate viscosity to other parameters:

$\frac{fD^3}{Q}$ and $\frac{fD^2}{\nu}$ and tested a 1" turbine with several viscosities fluids, showing a nice curve where all data lie along the same curve. Unfortunately he didn't show the error curve for this data. He even mentioned that "at low speeds the deviation occur due to bearing friction, enhanced by the radial loading of the magnetic pick up, no longer negligible compared to the fluid forces". At the curve of high viscosities, his conclusions were that even at the lowest speeds, 0,025f_{max} there is no "observable deviation from the curve, due to bearing friction, since the fluid viscosity is so high that the fluid forces remain large compared to the non-fluid forces, such as nonviscous bearing friction losses".

An interesting study was made by Lee (1960), also a reference in this field, showing that the driving torque of the turbine meter is proportional to ρQ^2, and, in steady state rotation it is equal to the total resisting torque of the rotating system of the meter.

The resisting torque was treated as consisting of two different torques: a total resisting torque due to mechanical friction (mainly bearing loads and register load) and a total resisting torque due to fluid drag .

According to Lee, "the term of resisting torque due to mechanical friction (bearings and register load) must be negligible even at the minimum flow rate for a turbine with high accuracy and repeatability". Lee made also the assumption that with very thin blades, the friction drag between the blade tip and the housing should be small because of small friction surface area. Also the friction drag in the spokes and hub can be designed to be very small. His paper paved the way to the explanation of the reasons that generate the shape of the curves.

Olivier and Ruffner (1992) made the statement that the Universal Viscosity Curve (UVC) is not a true representation of the actual flow through the turbine, and that a way to eliminate the errors of the UVC is to use the Strouhal (fD/V) and Roshko (fD^2/ν) numbers to plote the results. Most important is the alert to corrections due to temperature differences between calibration and operation, in the way it affects the diameter.

Mattingly (1992) produced a paper that showed that the UVC method has a series of limitations and advocates the use of dimensionless parameters, Reynolds, Strouhal and Roshko numbers, but the question of the use of the nonlinear portion of the curves was not the concern of his paper at that time.

Cuthbert and Beck (1999) launched a very interesting idea, that this paper has followed, that a computer can correct the nonlinearity at low flow rates using plots of dimensionless number like Reynolds, Stokes, Strouhal and a modified Strouhal number. They arrived to plots of (fd^3/Q) as a function of (fd^2/ν), the same it was used in this paper. They also produced curves with these dimensionless numbers using a 6th order polynomial and then plotted this in a log graph. In the present paper was used also a 6th order polynomial, but of the ln (fD^2/ν), which gives a better adjustment of the curves.

John Wright et al. (2011) used a polynomial adjust of 4th order of the log of the Roshko number to adjust data of several laboratories for the same turbines, using the fluid with the same viscosities, but treated data only for the linear range of the meters.

Pope, Wright and Sheckels (2012) made tests to extend the model developed by Lee, for three turbines (diameters of 25 mm, 19mm and 16 mm) and viscosities ranging from 1,2 centistokes to 14 centistokes. This is well within the limits of our tests. They recovered the model of Lee, calling it Extended Lee Model-ELM, to explain the influence of the viscosity on the turbine performance, consistent with the calibrations made using different values of viscosity. The curve of different viscosities coincide at large Reynolds numbers and spread out (fan) at lower Re values. The Lee model explains the "fanning" as a consequence of the bearing static drag.

They named the range of the calibration curve when the fanning occurs as "bearing-dependent range", as the bearings are responsible for the fanning phenomenon. They work out a model equation that represents the ELM, dependent of the angular frequency, flow rate, Reynolds number and several constants, and incorporates fluid drag and other Re-dependent forces on the rotor, bearing static drag and bearing viscous drag. The authors did not recommend performing multiple viscosities calibration to obtain the coefficients in their equation, due to possible change in the behaviour of the bearings along the time.

Their paper adjusts an average curve between the highest and lowest ν curves. With their mathematical model, in the bearing dependent region, using this average curve results in uncertainties ranging from 3,45 % to 4,76 %.

Experiments

Three turbine meters were tested in a compact prover calibrated by the weighing method, and its uncertainty in the range of flow rates used was determined as ±0,08 %. The compact prover was of the type operated with compressed air, and pushes the oil through the meter. The range of operation of the prover is from 0,005 to 90 m^3/h, and the minimum and maximum flow rates used in the tests were from 0,95 m^3/h to 65 m^3/h.

The turbines have nominal diameter of 25 mm, 40 mm and 50 mm. The 50 mm diameter was the only one with RF pick up. The others have magnetic pick-ups.

Three different oils were used to perform the calibration: HR-5 (7 cSt), HR-10 (17 cSt) and HR-20 (34 cSt).

The pipes and the prover were completely clean after every change of oil.

Data collection consisted at least 15 data points for every oil and every turbine, in a total of at least 45 data points per turbine.

The straight lengths downstream and upstream of the turbines were never smaller than 20D, D being the internal diameter of the turbine.

Data was collected in the so called linear part of the curve of K_{factor} as a function of flow rate, as well as in the nonlinear part up to the point where the frequency is very low but the turbine rotor still moves in a regular basis.

Calculation method

The results were plotted for all the three turbines in the following curves:

1. K_{factor} (pulses/dm^3) against flow rate (m^3/h);
2. K_{factor} (pulses/dm^3) against f/ν (Universal Viscosity Curve -UVC);
3. K_{factor} (pulses/dm^3) against f/ν using a 6th degree polynomial to adjust every data point to the curve, and its error curve;

4. K_{factor} (pulses/dm³) against f/ν using a family of functions, and its error curve;
5. fD^3/Q against fD^2/ν using a 6th degree ln curve fit, and its error curve;
6. fD^3/Q against fD^2/ν using a family of functions, and its error curve.

For curves type 3, when the parameters are $x = \left(\frac{f}{\nu}\right)$ and $y = K_{factor\text{-}est}$ (the estimated K_{factor}), the fitting of the data points was made by a polynomial of the type:

$$K_{factor\ est} = c_0 + c_1\left(\frac{f}{\nu}\right) + c_2\left(\frac{f}{\nu}\right)^2 + \cdots + c_6\left(\frac{f}{\nu}\right)^6$$

For curves type 4, when the parameters are $x = \left(f/\nu\right)$ and $y = K_{factor\text{-}est}$ (the estimated K_{factor}), the fitting of the data points was made by a family of functions of the of the type

$$K_{factor-est} = c_{-2}\frac{1}{\left(\frac{f}{\nu}\right)^2} + c_{-1}\frac{1}{\frac{f}{\nu}} + c_0 + c_1\frac{f}{\nu} + c_2\left(\frac{f}{\nu}\right)^2$$

For curves type 5, when the parameters are $x = \ln\left(\frac{fD^2}{\nu}\right)$ and $y = \frac{fD^3}{Q}$, the curve fit was of the type 6th degree polynomial:

$$\frac{fD^3}{Q} = \sum_{i=0}^{6} c_i\left[\ln\left(\frac{fD^2}{\nu}\right)\right]^i$$

For curves type 6, when the parameters are $x = \ln\left(\frac{fD^2}{\nu}\right)$ and $y = \frac{fD^3}{Q}$ the curve fit was of the type:

$$\left(\frac{fD^3}{Q}\right)_{estim} = c_{-2}\frac{1}{\left[\ln\left(\frac{fD^2}{\nu}\right)\right]^2} + c_1\frac{1}{\ln\left(\frac{fD^2}{\nu}\right)} + c_0 + c_1\left[\ln\left(\frac{fD^2}{\nu}\right)\right] + c_2\left[\ln\left(\frac{fD^2}{\nu}\right)\right]^2$$

The error should read:

$$Error = \left(\frac{k_{factor\ estim}}{k_{factor\ experim}} - 1\right)100$$

$$\frac{\left(\frac{fD^3}{q}\right)_{estim}}{\left(\frac{fD^3}{q}\right)_{experim}} - 1 \cong \left(\frac{Q_{experim}}{Q_{estim}} - 1\right)$$

Results

The results of the calibrations were analyzed in advance to the application of the mathematical adjustment, to purge the outliers clearly resultant of consistency. The main criterion was the minimum acceptable frequencies generated at the pick-ups, and the following limits were adopted: 29 Hz (f_{max}/f_{min}= 18), 36 Hz (f_{max}/f_{min}= 38) and 19 Hz (f_{max}/f_{min}= 29), respectively for the 25 mm, 40 mm and 50mm turbines.

The results were collected and some presented in the following sequence of figures. It is shown a complete set of the several curves obtained for the 50 mm turbine, and one curve of each other turbines.

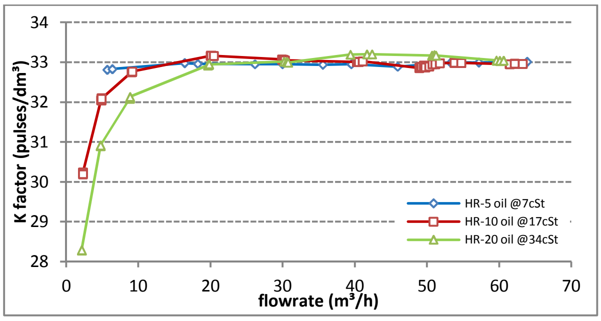

Figure 1- K_{factor} vs. flowrate for the 50 mm turbine

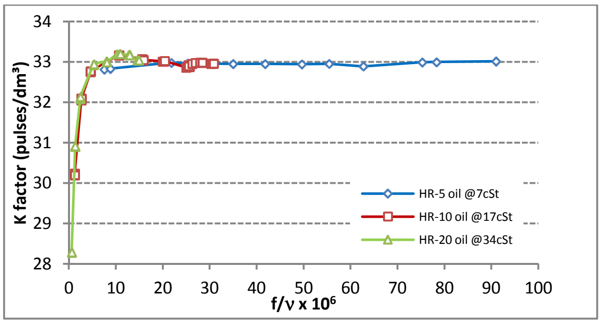

Figure 2 – Universal Viscosity Curve - K_{factor} vs. f/ν for the 50 mm turbine

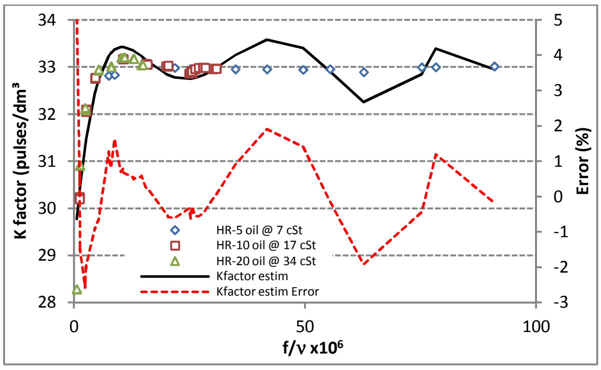

Figure 3 – Adjust of data points using a 6th degree polynomial for the Universal Viscosity Curve with all viscosities together for the 50 mm turbine. Error curve shown as dotted line.

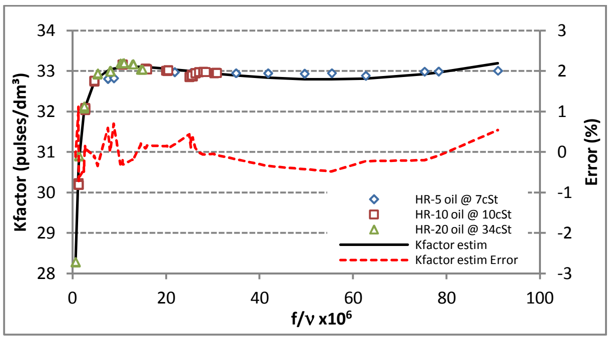

Figure 4 – Adjust of the data points for the Universal Viscosity Curve using the family of functions described

in the previous section for the 50 mm turbine. Error curve is shown as dotted line.

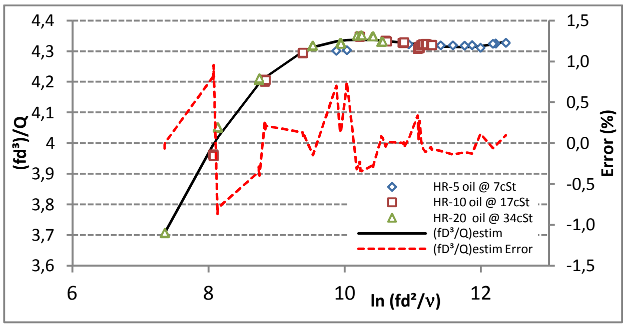

Figure 5 – Adjust of the data points using a polynomial function for (fD^3/Q) as function of $\ln(fD^2/\nu)$. Error curve is shown as dotted line for the 50 mm turbine.

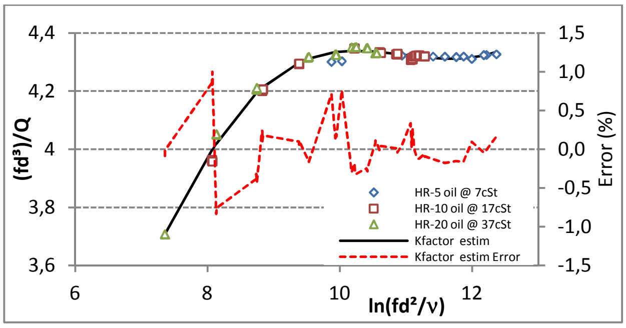

Figure 6 – Adjust of the data points using the family of functions to adjust the data points for (fD^3/Q) as function of $\ln(fD^2/\nu)$ for the 50 mm turbine. Error curve is shown as dotted line.

The following figures display the curves for the 6th order for the 25mm and for the 40 mm turbines.

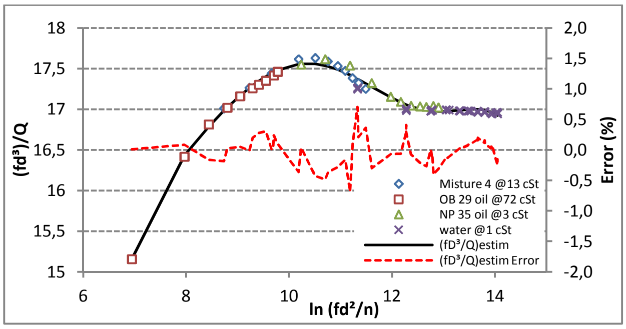

Figure 7 - Adjust of the data points for the 25 mm turbine using a polynomial function for (fD^3/Q) as function of $\ln(fD^2/\nu)$. Error curve is shown as dotted line.

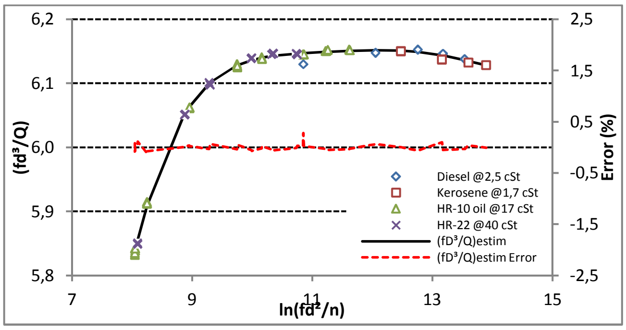

Figure 8 - Adjust of the data points for the 40 mm turbine using a polynomial function for (fD^3/Q) as function of $\ln(fD^2/\nu)$. Error curve is shown as dotted line.

The following table shows the uncertainty for the three turbines, using the three fluids with different viscosities (7 cSt, 17 cSt and 34 cSt). Curve 3 means UVC adjusted with a 6th order polynomial, Curve 4 is for the UVC adjusted for a family of functions, Curve 5 is for the polynomial function for (fD^3/Q) as function of $\ln(fD^2/\nu)$ and Curve 6 is for the family of functions adjusting the data points for (fD^3/Q) as function of $\ln(fD^2/\nu)$.

The estimation of uncertainty was taken as the combined fundamental uncertainty of the compact prover (0,08%, expanded) and the uncertainty of the curve adjustment, presented in Table 1.

Table 1 – Uncertainties for every turbine meter, for the linear range and for the whole data points (linear plus nonlinear range)

	Curve 3		Curve 4		Curve 5		Curve 6	
	U_{linear}	U_{whole}	U_{linear}	U_{whole}	U_{linear}	U_{whole}	U_{linear}	U_{whole}
T_{25}	1,6%	8,4%	1,2%	1,6%	0,7%	0,8%	0,8%	0,9%
T_{40}	0,2%	2,2%	0,2%	0,3%	0,2%	0,3%	0,2%	0,3%
T_{50}	0,6%	4,7%	0,6%	1,1%	0,6%	1,1%	0,6%	1,1%

Where: U_{linear} : Uncertainty in the linear range
U_{whole} : Uncertainty in the whole range
T_{25} : 25 mm turbine meter
T_{40} : 40 mm turbine meter
T_{50} : 50 mm turbine meter

Within the numbers of uncertainty calculated using curves 5 or 6, it is possible to define new ranges of operation as in table 2:

Table 2 – Range of operation within limits of uncertainty of curves 5 or 6.

	range	
	U_{linear}	U_{whole}
T_{25}	148:1	1200:1
T_{40}	63:1	340:1
T_{50}	20:1	150:1

Conclusions

The question that arises: is it possible to use only one curve to describe the behaviour of the turbine, allowing a certain degree of degradation of the uncertainty, within an expanded range of flow rates and in a large range of viscosities?

Perhaps the way it should go is to have a turbine meter calibrated with two fluids with very different viscosities, then make the adjustment of the data points to the 6th order polynomial for (fD^3/Q) as a function of $\ln(fD^2/\nu)$ or another good mathematical function for the case. Then, the flow computer may be programmed to perform the calculations.

For the three analysed turbines it is clear a difference in quality, the 40 mm being the most accurate, but it is also clear that a proper mathematical adjustment of data could improve a lot the range of operation for all the turbines, or at least allow a more educated guessing of the situation when there are expectations of large range of operation, or with a large range of viscosities.

The results have shown that two of the mathematical curves used (the 6^{th} order polynomial and the family of curves) to adjust data gave results that were good enough to improve dramatically the range of operation of the tested turbines, without losing quality. The 25 mm turbine may have a rage of operation of 1:1200 (uncertainty degrading from 0,8% to 0,9%), the 40 mm a range of 1:340 (0,2% to 0,3%) and the 50 mm a range of 1:150 (0,6% to 1,1%).

This approach may open possibilities to simplify the use of multiple viscosities operations with the same calibration curve in a large range of flow rate, which is the case in many operations in petroleum and chemical companies.

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