EFFECT OF REYNOLDS NUMBER IN CORIOLIS FLOW MEASUREMENT

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Abstract

In hydrocarbon measurement changing process conditions are the norm. Studies with highly viscous fluids have indicated there may be a shift in the calibration factor of Coriolis mass flow meter (CMF). According to those studies below a certain Reynolds (Re) number, the meter reads below the actual mass flow. In highly viscous fluids it’s possible to achieve low Re numbers with a sufficient mass flow.

As direct mass flow meters CMF are independent of the flow profile. Fluid structure simulations show that the shift is caused by an oscillatory shear or viscous effect in the CMF tubes due to the interaction between oscillating Coriolis forces and oscillating sheer forces. The ratio of these two forces is reflected in the Re number of the flow. This is a strongly deterministic effect only depending on the Re number.

Some CMF are able to measure the Re number. Subsequently a correction of the meter factor on-line would be possible, giving even higher accuracy under harshest conditions. This paper explains the mechanism behind this effect and presents data from different Coriolis meters ranging from 3” up to 14” showing how to ensure highest accuracy and repeatability for very low to high Re numbers. The importance of accuracy and repeatability is tremendous considering the amount and cost of hydrocarbons flowing through pipes each hour.

Introduction

When measuring hydrocarbon fluids strong variation of their properties – namely density, viscosity and compressibility – may occur. This band-width of physical properties can increase variations in the behaviour of the fluid flow in pipe lines. A Coriolis mass flow meter should be able to compensate such changes in fluid-flow and consequently measure within the accuracies as specified by the manufacturer.
Measurements data supporting a Reynolds number effect in Coriolis flow meter

The effect mentioned above has not been widely observed in the field, yet there are studies that imply it could also influence measurements by shifting the meter factor. TÜV/NEL carried out independent tests using different Coriolis and Ultrasonic flow meters of various manufacturers at temperatures between 10 and 40°C on miscellaneous viscous test fluids ranging from 1 to 300 cSt. The results published by Miller et al. in 2008 [1] showed under readings of Coriolis meters when measuring with very high viscous fluids (Figure 1).

When looking at Figure 1 one might draw the conclusion that the particular Coriolis sensor is not performing well for high viscous fluids, because the measurements show negative flow rate errors and a nonlinear behavior with a poor repeatability over temperature. For the low viscous fluids on the other hand the sensor measures within the stated performance. Similar behavior was found for other types of CMF.

**Figure 1:** 4” Coriolis Meter measurements of the four different test fluids (Kerosine 1-3 cSt), Gasoil (4-10 cSt), Velocite (10-30 cSt) and Primol (40-300 cSt) at temperatures between 10 and 40°C. Plotted is the mass flow rate error against flow rate. Figure from Miller et al. 2008[1].
Kumar et al. [6-7] suggested a shift of meter factor as cause induced by the interaction between oscillating Coriolis forces and oscillating sheer forces. The ratio of fluid dynamic forces for an oscillating system, such as a CMF with viscous fluid flow, is mainly characterized by a few dimensionless physical number e.g. Reynolds (Re) and Stokes (St) numbers.

Hence, if the data from figure 1 are plotted against Reynolds number, as it has been done by Mills, 2011 [2], the data look very deterministic (Figure 2). A shift in the meter reading with decreasing Re number is observed – indicating the presence of a fluid dynamic phenomenon responsible behind the shift. The correlation of the measuring offset with the Re number implies that if this CMF would process the Re number of every measuring point, it would be possible to correct the negative offset of the calibration factor itself using a distinct correction curve. The correction curve would solely be a function of the Re number.

![Figure 2: Coriolis Meter mass flow error plotted against Reynolds number [Mills 2011]. A shift in the meter reading with decreasing Reynolds number can be observed indicating the presence of a fluid dynamic phenomenon responsible behind the shift.](image)

Being aware of this situation, Coriolis meter manufacturers started to investigate the observed effect. Experimental results support the findings from TÜV/NEL. Is there a way of explaining the effect and can it be compensated? Conventional meters, such as turbine meters, or advanced measurement principles, such as ultrasonic meters, are more influenced by a change in Re number than Coriolis meters. [1, 10]
Understanding the mechanism

Experiments with different types of CMF featuring various designs and tube shapes with highly viscous fluids seem to support the theory that there is a shift in the calibration factor towards lower Re numbers. Further considerations suggest that this effect is not due to the viscosity of the fluid itself, but with high viscous fluids it is possible to achieve low Reynolds numbers with a moderate flow velocity. It should be noted that the shift is often wrongly attributed to the change in flow-profile in the measuring line. However, it is important to keep in mind a CMF, as a direct mass flow meter, is entirely independent of the nature of axial flow profile in the measuring tube.

As far as Coriolis flow meters are concerned, there are a few attempts to simulate a CMF using coupled fluid–structure interaction (FSI) approach. Kutin et al.[3-5] mainly investigated flow profile effects in straight-tube Coriolis meters. According to their research the present effect is due to the change in axial flow profile, because of the variation in the Reynolds number. Kutin et al. [3-5] attributed the shift in meter readings with respect to decreasing Re numbers to the change in axial flow profiles from turbulent to laminar transitions.

Kumar et al. [6] studied the mechanism which is behind this shift using the help of coupled FSI simulations of real Coriolis meter designs and compared with the experimental data of the same device. From Figure 3 it may be noticed that the numerical simulations qualitatively support the experimental observations.

Figure 3: A comparison between experimental and numerical simulation results indicating a shift in meter calibration factor in low Reynolds number region from [Kumar et al. 2010]

Kumar et al. [6-8] investigations suggest that the effect is the result of an interaction between the oscillatory shear force and the inertial Coriolis force in the measuring tube, leading to an oscillatory secondary flow. At a given time, this secondary flow moves in opposite directions in either sides of the tube center and disappears at the center of the
tube. The ratio of the two oscillating forces is directly proportional to the Re number of the mean flow. The secondary flow at a Re number of 100 is shown in Figure 4a. At sufficiently high Re number this secondary flow disappears and consequently the ratio of shear force to Coriolis force becomes negligibly small.

Figure 4: (a) The computed oscillatory secondary flow in moving-frame of reference at the position where sensor is located, (b) a schematic representation of the oscillatory mechanism responsible for Reynolds effect.

Since this effect of the secondary flow appears at the outer layer near the tube wall, it is sometimes also called “boundary layer effect”. The phenomenon behind is briefly described with the help of a schematic diagram in figure 4b. As shown there, the Coriolis force interacting with the shear force induces an asymmetric force in the measuring tube. The lower two panels illustrate that the Coriolis force induces a shear layer indicating a secondary circulation in the cross-section of the measuring tube. The Coriolis force has to overcome the shear force and part of the energy of the Coriolis force is dissipated in the secondary circulation and does not contribute to the deflection of the tube. This explains why the meter reading is below the actual mass flow. The magnitude of the secondary circulation is strongly decreasing with higher Re numbers as the thickness of the shear-layer decreases exponentially with the increasing Re number. Consequently, the effect becomes insignificant above a certain Re number.
It is important not to confuse these oscillatory viscous or shear force with the steady shear force exerted by the fluid on the pipe-wall. In a Coriolis meter, steady fluid-dynamic forces cannot influence sensitivity of the meter. In order to influence the meter reading, the force (e.g. viscous or shear force) has to be oscillating in nature and moreover the periodicity of this force has to be matched with the periodicity of the pipe oscillations.

**Real time correction for the Reynolds effect**

In order to meet highest accuracy requirements in low-Re applications, the Re number effect must be compensated.

The Re number is calculated as

\[ \text{Re} = \frac{VD}{\nu} = \frac{\rho V D}{\eta} = \frac{4\dot{m}}{\pi \eta D} \]  

where \( V \) is the mean flow velocity, \( \rho \) the fluid density, \( D \) denotes the internal diameter of the pipe, \( \dot{m} = \frac{V \rho}{D^2 \pi / 4} \) the mass flow rate, \( \nu \) the kinematic and \( \eta = \nu \rho \) the dynamic viscosity.

A CMF usually measures the mass flow rate and density. Therefore the only unknown variable in eq. 1 is the viscosity which can be measured as well by some CMF [Rieder et. al 9] Hence, if a Coriolis meter has the ability of deriving a measure for viscosity directly, compensation can be done on-line by on-board means. However, this is a patented feature.

**Measurements with different meters over a wide Reynolds number range**

In the following figures witnessed measurements of Coriolis flow meter of the size 3”, 4”, 6”, 10” and 14” are shown using on-line Re effect compensating. These measurements were performed at TÜV/NEL (3”-6”) and SPSE (10”-14”), using different hydrocarbons ranging from Kerosene over mineral and crude oils to heavy bunker fuels. Each meter was measured over its whole flow range with at least two different fluids with strongly different viscosities. The viscosity range reached from 0.7 up to more than 1000 cSt. By varying the flow rate and the viscosity a huge Re number range from 100 up to 5,000,000 could be covered.

In figure 5 the measuring performance of the Coriolis meter is plotted against Re number. In this plot no shift in the meter reading with decreasing Re number can be observed.
Figure 5: Coriolis Meter mass flow error of 5 different sizes plotted against Reynolds number. Measurements were performed at TÜV/NEL (3”– 6”) and SPSE (10” and 14”). Measuring performance is meeting accuracy requirements of OIML R117-1 class 0.3.

These measurements demonstrate that Coriolis devices are able to meet the accuracy requirements of OIML R117-1 class 0.3 over a very wide range of fluids.

In figure 6 the same data is plotted against kinematic viscosity. In this figure no viscosity effect can be observed.

Figure 6: Coriolis Meter mass flow error of 5 different sizes plotted kinematic viscosity. Different hydrocarbons were measured ranging from naphtha and kerosene over crude oils to heavy bunker fuels. Each meter was measured with at least two different liquids with strongly distinct viscosities. The range of the viscosity reached from 0.7 up to more than 1000 cSt.
To sum up all of the above and give an indication about the abilities of the tested meters in hydrocarbon measurement, figure 7 shows the relative mass flow error over the mass flow rate. The measurement results bear testimony of the first-rate qualification and measurement performance of CMF in hydrocarbon measurement.

**Figure 7:** Coriolis Meter mass flow error of 5 different sizes plotted against mass flow rate. Each meter was measured over its whole flow range with at least two different liquids with strongly distinct viscosities.

**Conclusions**

Although a Coriolis mass flow meter is independent of flow profile or installation effects, studies suggested that it may be dependent on the Reynolds number of the mean flow. With the help of fluid-structure interaction simulations, the mechanism responsible for the Reynolds effect in CMFs can be elucidated. It has been shown that the Reynolds effect may induce a secondary flow in the oscillating tubes of CMF. The oscillatory secondary flow would lead to a change in the sensitivity of the flow meter. The meter deviation can be corrected in-line in the flow meter provided the mass flow and viscosity are known.
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References


