System and Methodology for liquid ultrasonic flow measurement within laminar to turbulent transitional zone

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Abstract

Applications for liquid ultrasonic Custody Transfer flow measurement are traditionally limited to flow ranges within the meter's performance capability related to the viscosity of the fluid, particularly in the low Reynolds number region where the flow range is across the laminar, transitional and turbulent flow regimes. This paper discusses new methodology by which the flow meter's performance can be extended into lower ranges of Reynolds numbers for viscous flows while maintaining the close tolerances needed for Custody Transfer measurement applications. The methodology includes the ability to dynamically measure the Reynolds number as well as the fluid's kinematic viscosity within the laminar to turbulent transition zone.

Introduction

Industry acceptance of ultrasonic meters is driving the growth of this technology into a wide range of measurement applications. Ultrasonic meters are widely used in custody transfer and many other flow measurement applications, such as carbon dioxide, waxy crude oils, and even cryogenic fluids (liquid natural gas and liquid nitrogen), to measure the flow rate of liquid and gas flowing through pipelines.

Ultrasonic meters make velocity measurements using the time of flight technique along discrete narrow paths within the pipe cross section known as chords, which are then combined according to the presumed velocity profile to integrate and compute the volumetric flow rate [1]. This approach works successfully in the well developed turbulent region where the Reynolds number (Re-defined below in Equation 1) based on pipe inner diameter is well above 35000.

$$Re = \frac{\rho U D}{\mu}$$

Equation 1

Where ρ is density,

U is the mean velocity across the pipe cross section,

D is the pipe diameter, and,

μ is the dynamic viscosity of the fluid.

Variation of flow velocity along the cross-section inside the pipe (or an ultrasonic flow meter) is parabolic for fluid flow when the flow is laminar in which Re<≈2300, The flow becomes transitional approximately when 2300<≈Re<≈5000, and is turbulent in most applications when Re>≈5000. However, the Re for fully developed turbulent flow is approximately above 35000. The turbulent mean velocity profile has a much flatter velocity distribution in the core region (central portion) of the pipe and a steep gradient near the wall. This is significantly different from the parabolic mean velocity profile. There are number of initial stages of development in the turbulent mean velocity profile between 5000<≈Re<≈15000, which includes initial stages of mean velocity profile, and initial stages of turbulent statistics. Turbulent flow generally requires a significant scale separation between large and small scales (or a significantly large Re) to attain a fully developed state [2,3,4]. A detailed view of changes in the mean velocity profile for liquid ultrasonic meter measurements compared with computational fluid dynamics results is shown in Figure 1. The abscissa of this figure is the normalized mean velocity and the ordinate is the normalized distance from the pipe central axis.

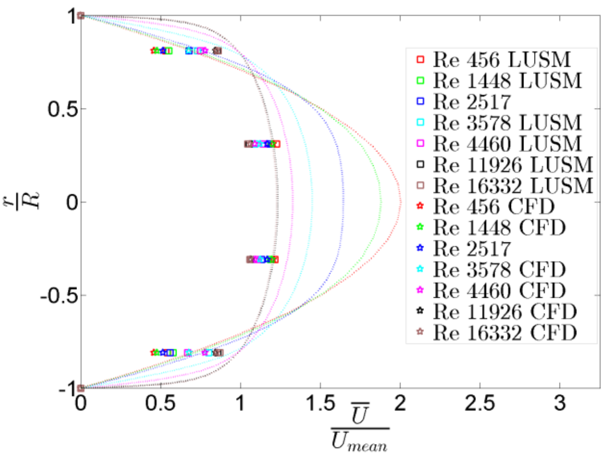

Figure 1 : Variation of mean velocity profile with Reynolds number

Ultrasonic flow meters essentially measure the velocity profile inside a pipe at pre-determined radial positions based on their adopted integration technique [5]. The velocity profile is dependent on flow regime as the Reynolds number based on pipe inner diameter decreases down to laminar flow region. Therefore, the volumetric

[1, 2, 3, 4] Daniel Measurement and Control, 11100 Brittmoore Park Dr, Houston, TX 77041 flow rate measurement error increases rapidly as the flow regime is changed from turbulent flow to laminar flow as shown in Figure 2. Daniel® specifies a linearity of ±0.15% for a liquid ultrasonic meter over its flow range for custody transfer applications [6]. The International Organization of Legal Metrology specifies a linearity of ±0.2% for class of 0.3 meters [7]. Ultrasonic meters are factory corrected at the time of initial calibration within the turbulent regime by application of a calibration function to the flow laoratory's standard of traceability for flow measurement. The raw error curve may be corrected with a constant deviation or with a constant gradient in the turbulent region in the initial calibration. The non-linear error curve shown in Figure 2 is extremely difficult to correct using a single function and matching the performance for a field application is a challenge. Therefore, it is very difficult to implement liquid ultrasonic flow measurement in low Reynolds number regimes consisting of laminar, transitional and preliminary turbulent flows.

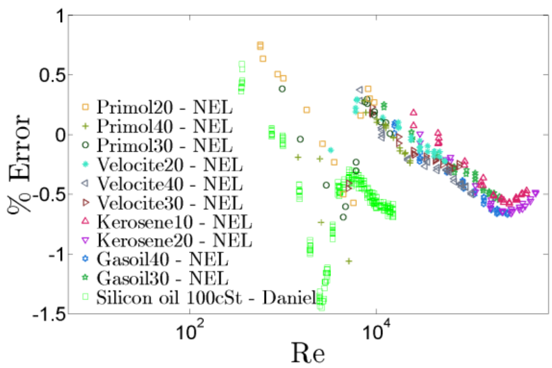

Figure 2: Liquid ultrasonic meter flow rate measurement error in low Reynolds number regime

Conventional metering configuration

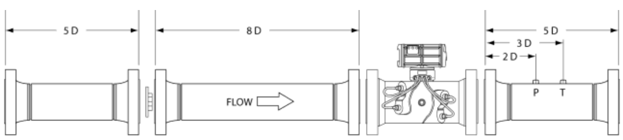

Figure 3: Conventional liquid ultrasonic meter installation

Figure 3 shows a typical liquid ultrasonic flow meter installation, where there is a straight pipe section of 5 diameters upstream followed by a flow conditioner and a straight pipe of 8 diameters just upstream of the liquid ultrasonic flow meter. There is a pressure and a temperature transmitter 2 and 3 pipe diameters downstream of the liquid ultrasonic meter as shown respectively. It is possible to obtain a reasonably well developed chordally averaged velocity profile using this conventional piping methodology. This setup also creates reasonably well developed laminar and turbulent chordally averaged mean velocity profiles which lead into strongly non-linear error curves for low Re, as shown in Figure 2.

Proposed metering configuration

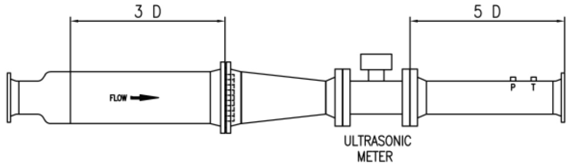

Figure 4: Proposed metering configuration

Figure 4 shows the proposed metering configuration, where the first section is expanded from an upstream pipe line, followed by a straight pipe at least 3 upstream pipe diameters long. A flow conditioner follows, then a special reducer. The liquid ultrasonic meter is flush mounted accurately to the downstream end of the special reducer. Pressure and temperature transmitters are located downstream of the liquid ultrasonic flow meter.

Results

Figure 5 shows the corrected volumetric flow rate measurement error from the proposed metering system and methodology. As shown, the corrected error curve remains well within ±0.15% for Reynolds number up to and above 3000. There is some scatter below Re<3000. The data in the region 500<Re<3000 indicate additional scatter; however, the corrected volumetric flow rate measurement error remains well within ±0.2%.

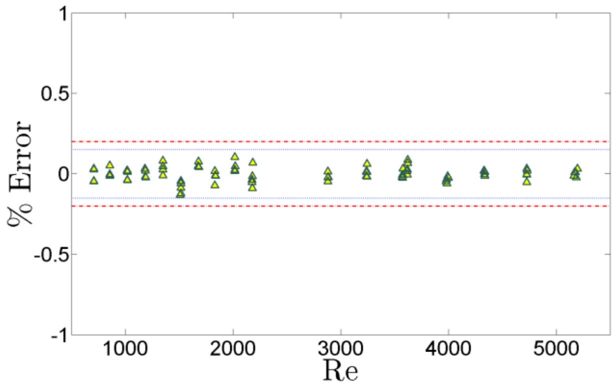

Figure 5: Corrected volumetric flow rate error

The liquid ultrasonic flow meter with the proposed metering configuration can measure kinematic viscosity; a separate viscometer is not required. The error in viscosity measurement is shown in Figure 6 and is within ±3% for Re>2000 and is within ±5% for 500<Re<2000.

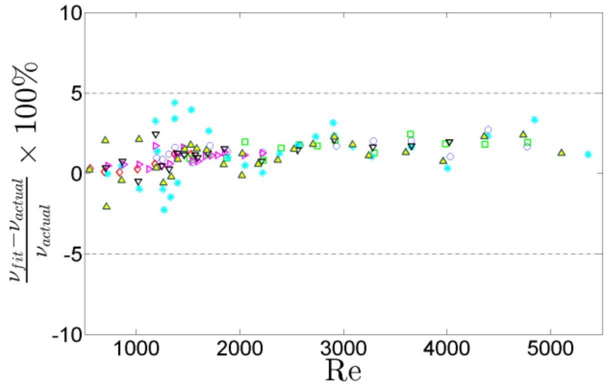

Figure 6: Error in kinematic viscosity measurement

Using the kinematic viscosity measured above, along with the mean velocity from the liquid ultrasonic meter and the nominal pipe diameter it is possible to compute the Reynolds number for the meter bore. The error in Reynolds number computed by the meter against actual Reynolds number is shown in Figure 7. As shown, the error is within ±3% for Re>2000 and is within ±5% for 500<Re<2000. This data provides information for diagnosis of meter performance and fluid flow phenomena in the field application.

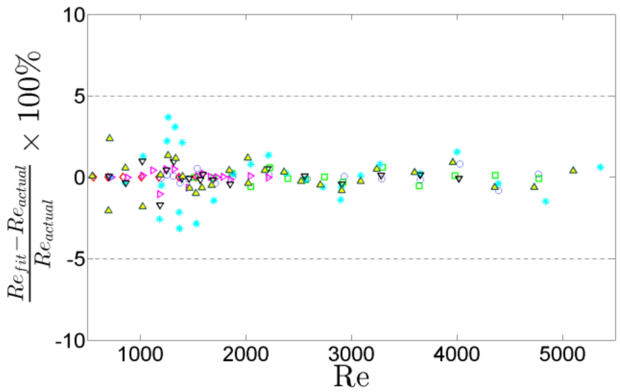

Figure 7: Measurement error in Reynolds number

Conclusion

It is possible to extend the lower cut-off Reynolds number for liquid ultrasonic meter performance at very low Reynolds numbers into the laminar flow regime using the newly described methodology of flow conditioning. Furthermore, the liquid ultrasonic flow meter can provide indication of liquid viscosity and Re in the low Re range with the same methodology.

References

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