Dynamic Testing

Authors:
Raymond J. Kalivoda
Jim H. Smith
Nicole L. Gailey

ABSTRACT

Dynamic factory testing is an important step in the manufacturing of ultrasonic meters for custody transfer and other high accuracy petroleum applications. By utilizing a multiple product, high accuracy test system and a proper test program, a meter's performance can be simulated over a wide flow and viscosity operating range. The test results give the user a detailed graph of the meter's performance over the actual site operating parameters. The test verifies the meter's performance prior to shipment but more importantly provides K-Factor sensitivity to optimize measurement accuracy throughout the operating range. This paper outlines the theoretical basis and fundamentals of dynamic testing. It illustrates the process with data from an ultrasonic meter factory test recently conducted for a North Sea operating company. The meter was a 12 inch multi-path ultrasonic meter operating over a flow range of 636 to 1,113 m^3/h (~ 4,000 to 7,000 BPH) and a viscosity range of 5 to 350 cSt.

The details of dynamic testing and the relationship between the measurement accuracy of a meter and dynamic testing will be the focus of this paper. It will include:

- The fundamental operating principle of ultrasonic meters
- Fluid dynamic properties such as boundary layer and flow profiles
- The characteristics of the flow profiles in the different flow regimes that affect crude oil measurement
- The dynamic operating range of crude oil meters
- How dynamic testing is used in factory testing to verify the performance of a meter
- Results of the 12 inch multi-path ultrasonic meter factory testing

This paper will provide the necessary information to fully understand the basis and proper methods for dynamic testing to determine the operating performance of an ultrasonic meter.

1. INTRODUCTION

As the world oil supply of heavier crude oils increases, in conjunction with an increase of use of liquid ultrasonic meters, testing by the manufacturer plays a critical role in the meter performance verification for the end product customer. If the meter manufacturer has their own flow test facilities, this can save significant time and cost in the delivery of the meter. Dynamic testing or Reynolds Number testing has been used for manufacturing and testing of helical turbine meters since their acceptance into custody transfer applications in the mid-1990's. While the Reynolds Number performance between helical meters and ultrasonic meters are different, the dynamic test programs are very similar. By utilizing an ISO 17025 accredited, multiple product test system and a proper test program, a meter's performance can be simulated over a wide flow and viscosity operating range.

2. LIQUID ULTRASONIC METER OPERATING PRINCIPLE

Liquid Ultrasonic meters were initially used in the petroleum industry for non-custody applications. But with the advances in microprocessors, transducer technology, electronics, and the introduction of multi-path meters, transit time ultrasonic meters can provide accurate measurement over a wide range of applications. This includes custody transfer of high viscosity crude oils. Ultrasonic meters, like turbine meters are inference meters. They infer the volumetric through-put by measuring the velocity over a precise known flow area. As with all velocity inference meters, they are Reynolds Number dependent. That is, they are affected by the relationship between velocity, flow area, and viscosity. The fundamental difference between ultrasonic and turbine meters is that the former uses non-intrusive ultrasonic signals to determine velocity and the later an inline helical rotor. Since Reynolds Number was developed for free flowing pipes, its principles can be best illustrated with ultrasonic meters.

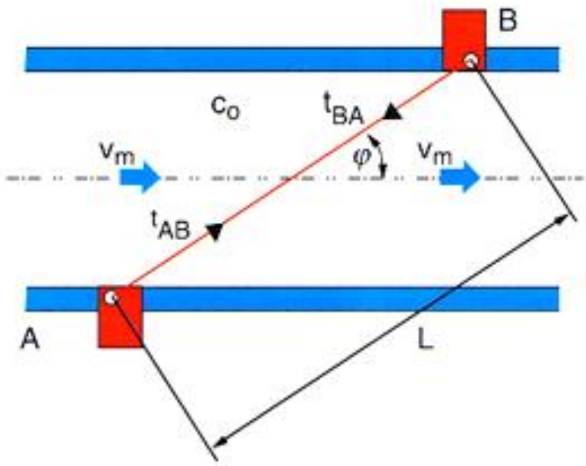
As a review of the operating principle, ultrasonic meters derive flow rate by calculating an average axial flow velocity in the pipe. This is done by summing the individual path velocities in the meter and then multiplying it by the flow area in the meter throat as shown by the following equation:

$$Q_{total} = A * \sum_{i=1}^{n} w_i v_i$$

Q_{total} = Volume flow rate; A = Inside diameter; *v* = Path velocity; *w* = Chordal path weighing factor

The flow area in the equation is the physical geometric area based on the meter's inside diameter which is measured and input as a programmed parameter. However, the effective flow area is one that is formed by the meter inside diameter and the boundary layer which is influenced by the pipe wall roughness, fluid viscosity and velocity at operating conditions. All which will affect the flow profile shape. This will be discussed later.

The individual path velocity of a non-refracting configuration is determined by measuring the difference in transit time of high frequency acoustic pulses that are transmitted with the flow (A to B) and against the flow stream (B to A) at a known angle and length (Figure 1). The ultrasonic signals are generated by piezoelectric transducers that are positioned at an angle to the flow stream. It is, therefore, imperative that a high quantity and quality of signals propagate through the fluid medium to achieve a good representative sample. Some manufacturers can supply different sets of transducers that operate at higher or lower frequencies to extend the application viscosity and improve signal quality.



$$T_{AB} = \frac{L}{c + v\cos(\theta)}$$

$$T_{BA} = \frac{L}{c - v\cos(\theta)}$$

$$c = \frac{L}{2} \cdot \frac{T_u + T_d}{T_u T_d}$$

$$vm = \frac{L}{2\cos(\theta)} \cdot \frac{T_u - T_d}{T_u T_d}$$

Figure 1: Single Path of a Non-refracting Transducer Pair

The principle of ultrasonic measurement is simple. However, accurately determining the average velocity and the effective area under different operating conditions can be difficult. Especially when attempting to obtain custody transfer measurement accuracy over a wide dynamic range. The difference in time between the two transducers can range between tens or hundreds of picoseconds for typical liquid ultrasonic flow meters (depending on meter size and fluid density). The minimum time difference is tied to the lower flow limit and the maximum time difference to the upper flow limit of the meter. Detecting and precisely measuring these small time differences is extremely important to measurement accuracy and each manufacturer has proprietary techniques to achieve this measurement. Velocity profiles are highly complex and one set of transducers only measures the velocity along a very thin path which represents only a sample of the total flow across the meter area. To determine the velocity profile more accurately, custody transfer ultrasonic meters use multiple sets of transducers on chordal paths. The multiple chordal paths help in detecting whether the flow is laminar, transitional, or turbulent. The number of paths, their location, and the algorithms that integrate the path velocities into an average velocity all contribute to the meter's accuracy.

Besides the axial velocity there are transverse velocity components (swirl, cross flow) as well. These components of flow may be caused by two out-of-plane bends or other piping configurations, as well as local velocities at the transducer ports. Both the swirl and cross flow components are included in the path velocities. The local velocities are normally symmetrical and can be statistically cancelled. The transverse velocity components should be eliminated or minimized by flow conditioning and must be accounted for by the meter through measurement. Some ultrasonic meter designs measure the transverse velocity and account for it in the axial velocity algorithms.

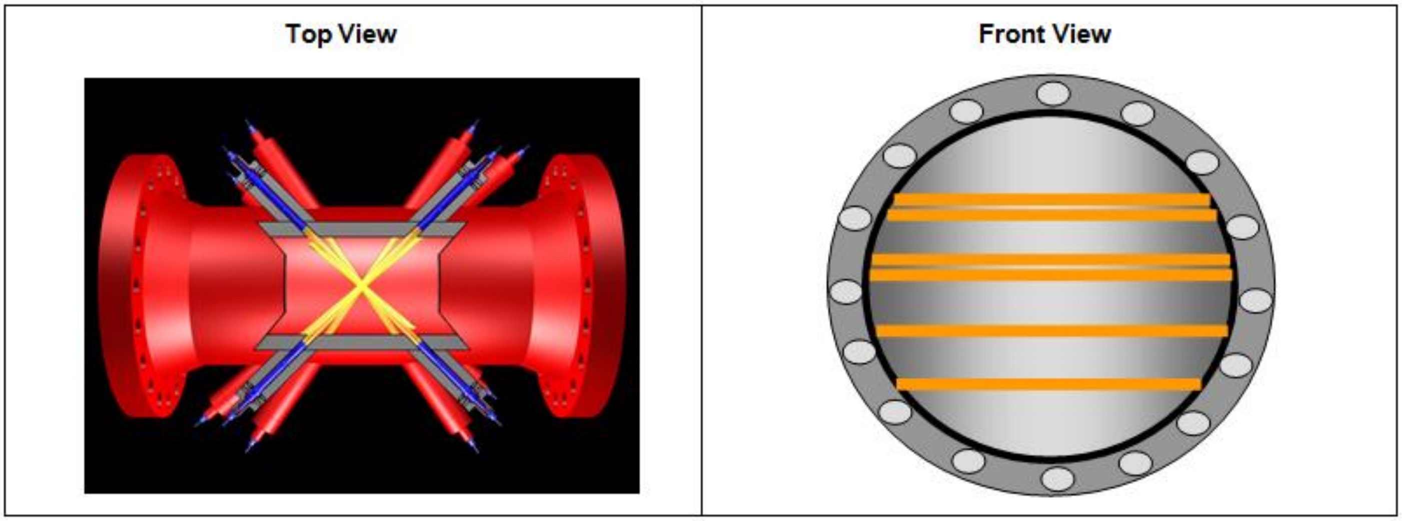


Figure 2: Multi-path Non-refractive Chordal Ultrasonic Meter

3. BOUNDARY LAYER AND FLOW PROFILES

The flow area is dependent on the meter inside diameter which is a physical measurement of the meter housing. The effective area is dependent on boundary layer thickness and can be seen in Figure 3 as the diameter of the flatter region of the profile. The boundary layer thickness at the pipe wall is influenced by the pipe roughness, viscosity, and velocity of the metered fluid. Looking at Figure 3 from left to right, we can see various representations of flow profiles and boundary layer thicknesses. As the velocity decreases or the viscosity increases, the boundary layer increases which reduces the effective flow area. At high flow rates with low viscosity fluids, such as refined products or light crude oils, the boundary layer thickness is very small (shown in Figure 3 on the right). This produces a flat shape velocity profile across the pipe inside diameter.

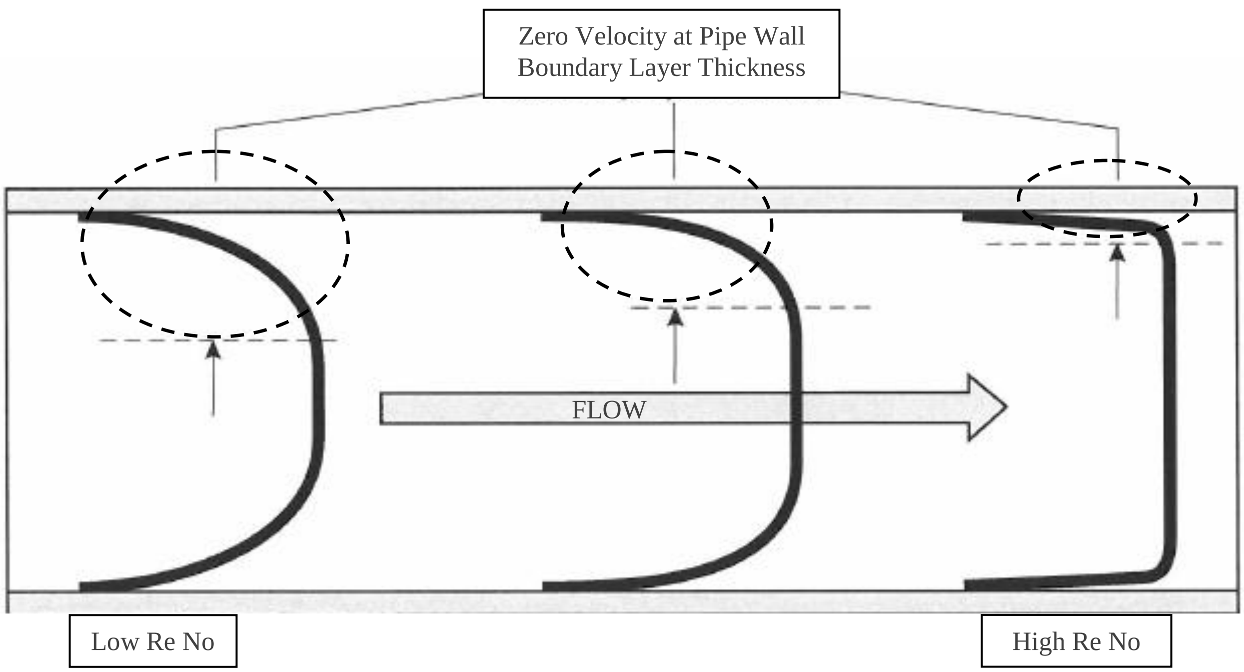


Figure 3: Boundary Layer Influence on Flow Profile and Reynolds Number
*** Per API MPMS, Ch. 5.8 [1] (Annex D)**

The boundary layer also defines a specific velocity profile. Determining the profile and compensating for its effect on the calculated axial velocity is the key factor in the manufacturing of highly accurate ultrasonic meters that are used over a wide dynamic range. The relationship of the velocity flow profile and flow area is quantitatively defined by Reynolds Number (Re No) and Dynamic or Reynolds testing is the method used to determine ultrasonic meter performance.

4. REYNOLDS NUMBER AND FLOW PROFILE

The shape of the velocity flow profile is the result of the viscous forces (viscosity) that constrain the liquid's inertial forces (velocity • density). When the viscous forces are greater than the inertial forces, the flow profile becomes parabolic in nature. As the inertial forces become greater than the viscous forces the flow stream becomes highly turbulent which produces a flat plug type flow profile. The parabolic shape of the flow profile is determined by the thickness of the fluid boundary layer at the pipe wall. Regardless of the flow rate and product viscosity, the velocity at the pipe wall will be zero. The maximum axial velocity is at the center of the pipe, unless there are hydraulic influences from elbows, reducers, or the other types of upstream disturbance which produce asymmetric profiles (maximum velocity off center).

At a low Reynolds Number the viscous forces constrain the initial forces, forming a greater boundary layer and parabolic flow profile. But as the Reynolds Number increases due to an increase in velocity or decrease in viscosity the boundary layer at the wall is reduced and the flow profile becomes flattened as shown in Figure 3. In fluid dynamic terminology the parabolic flow profile is defined as laminar flow and is mathematically designated by the dimensionless Reynolds Number as less than 2,000. The flat or plug shaped flow profile is defined as turbulent flow with a Reynolds Number of greater than 4,000 to 8,000. The exact Reynolds Number which defines the turbulent flow regime is dependent upon the upstream piping and other dynamic factors. Between laminar and turbulent flow, transition flow occurs and the velocity profile changes rapidly between laminar and turbulent. Over a wide Reynolds Number, transition occurs in a very narrow range.

An interesting fact determined by Osborne Reynolds over 120 years ago and repeated in thousands of experiments since, is that the boundary layer and flow profile will always be the same at the same Reynolds Number. This is illustrated in Figure 4 where three conditions are shown with different flow rates and viscosities but the same Reynolds Number. In this case, we can use flow rate divided by viscosity for the Reynolds Number comparison. Therefore, the ultrasonic meter's field performance can be accurately duplicated by Dynamic or Reynolds Number testing in a flow lab that is capable of producing the same range of application. This provides a sound means for verification and calibration where field conditions cannot be replicated. This is especially true with very large meters where it is not feasible or economical to achieve the high flow rates and high viscosities associated with large meter specifications. This is a common limitation in test facilities around the world.

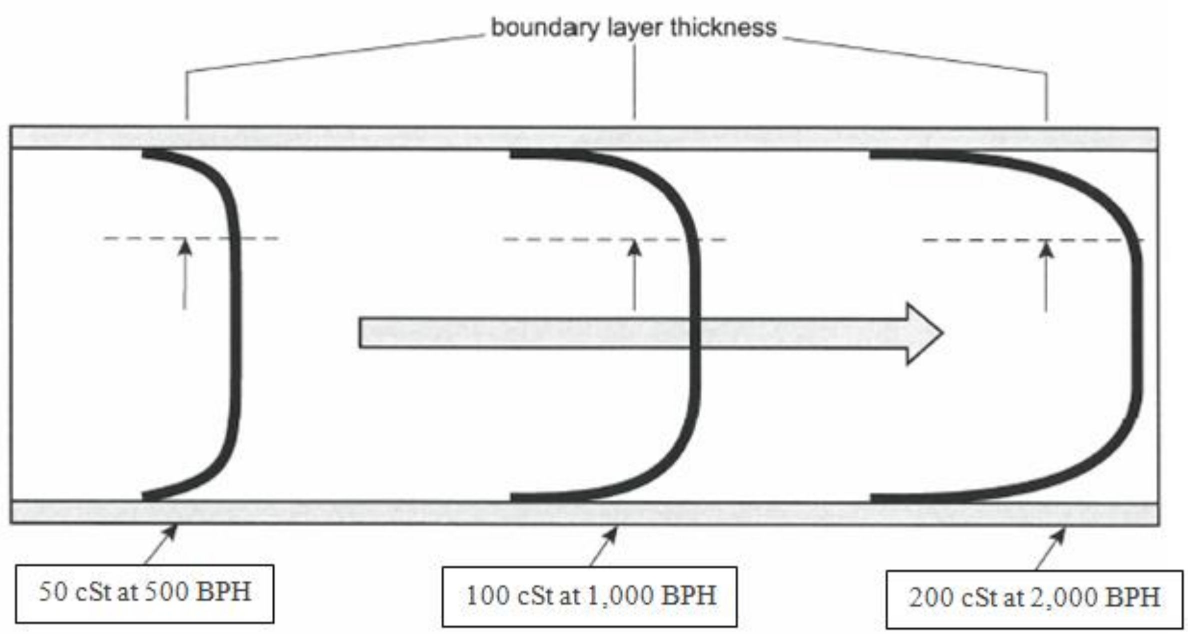


Figure 4: Velocity Profile Dynamic Similitude with Reynolds Number
*** Per API MPMS, Ch. 5.8 [1] (Annex D)**

5. DYNAMIC FACTORY TESTING

An important step in the manufacturing of custody transfer and other high accuracy petroleum meters is the factory flow test. Conventional meters such as positive displacement (PD) and turbine meters (inference meters) are typically tested on a light petroleum fluid (2 cSt to 4 cSt) over a specified flow range to verify that the meter's performance meets specifications. Validation of the meter occurs in the field by proving the meter in-situ under operating conditions. This is typical for meters up to 16 inch in size.

The performance of ultrasonic meters for light product applications can be determined from low viscosity factory tests. If these meters are to be applied over a wide viscosity range they must be tested over both a flow and viscosity range. This flow and viscosity range is what's known as the "dynamic performance range". This is especially true for ultrasonic and helical turbine meters which will be subject to heavy crude oils. The ultrasonic meter requires the development of a special algorithm to compensate for the effect of viscosity on flow profile, where a helical turbine meter requires the "tuning" of its rotor to operate accurately within the operating conditions. The accuracy of the factory dynamic test will determine how well these meters perform under actual operating conditions.

Because of the unique operating characteristics of ultrasonic meters in crude oil applications it is necessary to develop new dynamic factory test protocols. These methods are different than traditional factory testing. They provide a greater level of confidence that the meters will fully meet the performance requirements over the complete operating range.

All dynamic tests are developed from Reynolds Number which can be defined as the following:

$$\text{Re No} = \frac{(K \cdot \text{Flow rate})}{(\text{Meter Size} \cdot \text{Viscosity})}$$

- K = 2,214; a constant for flow in barrels per hour (bph)
- K = 13,925; a constant for flow in cubic meters per hour (m^3/h)
- Meter size = bph or m3/h meter sizes in inches
- Viscosity = Kinematic Viscosity [1 centistokes = 1 millimeter squared / second (mm^2/s)]

Typical Reynolds Number ranges for hydrocarbon products are displayed in Figure 5. The low viscosity products produce high Reynolds Numbers and have more predictable results. Therefore by obtaining water test data at 0.6 cSt at 40°C (104°F) it is possible to accurately predict the performance on a Liquid Petroleum Gas (LPG) at 0.3 cSt.

The same is not true for high viscosity products, such as medium or heavy crude oils. The Reynolds Number plot is inherent to the meter size, type, flow range, and viscosity range where the deviation in meter factor from a light crude oil to medium or heavy crude oil can be 2% to 5% or even greater prior to compensation. The only way to develop the proper correction and validate the meter's performance over this range is to dynamically test the meter over the same Reynolds Number range.

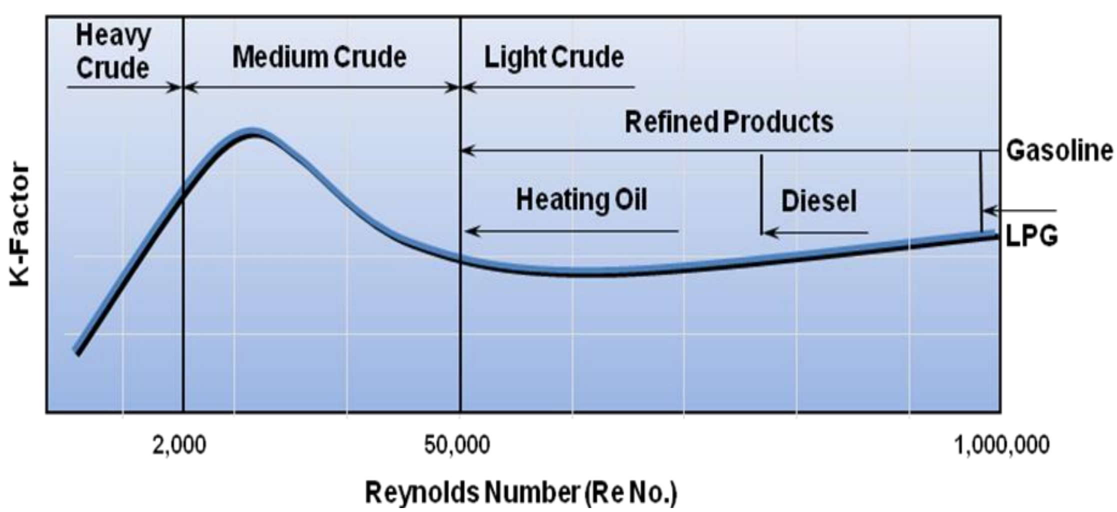


Figure 5: Reynolds Number Ranges for Petroleum Products

6. DYNAMIC TEST EXAMPLE

The following example will best illustrate the methodology of Dynamic or Reynolds Number Testing. Table 1 shows the field operating conditions for three sizes of multi path ultrasonic meters – 6, 12, and 20 inch (150, 300, and 500 millimeter) with their flow ranges and products at 800 cSt and 1,000 cSt respectively. The table also shows these operating conditions expressed in Reynolds Number.

Table 1: Example of Field Operating Conditions

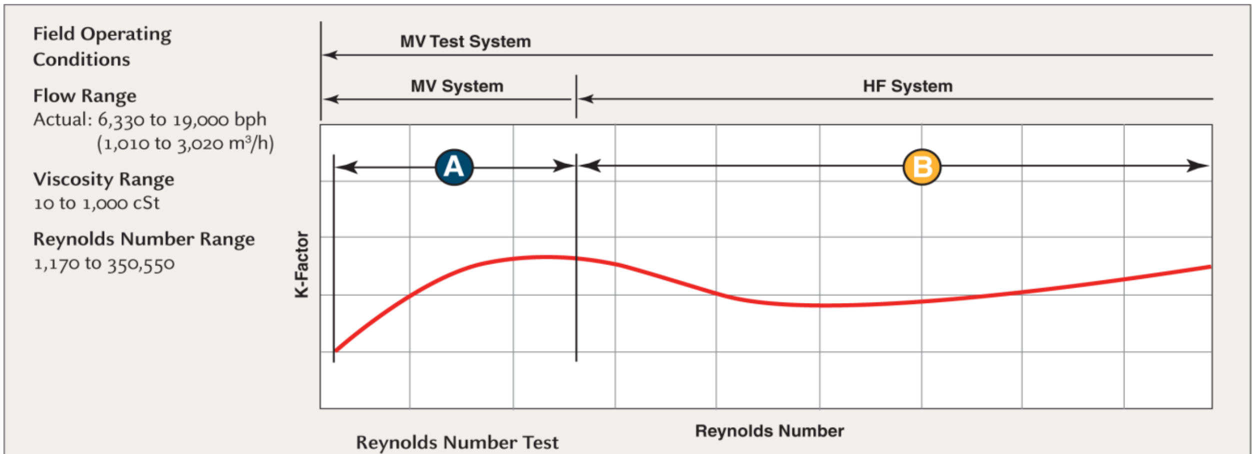
Meter (Inches)	Flow Range			Viscosity (cSt)	Reynolds Number Range	
6	bph	1,500	4,500	800	690	2,080
	m3/h	240	720			
12	bph	6,330	19,000	1,000	1,170	3,510
	m3/h	1,010	3,020			
20	bph	14,000	42,000	1,000	1,550	4,650
	m^3/h	2,230	6,680			

Utilizing the field operating conditions, factory testing is developed based on the available test fluids and test system flow ranges. Table 2 shows the tests that satisfy the dynamic operating range of the meters in Table 1. This can be confirmed by observing that the Reynolds Number ranges are the same. This method of dynamic similitude allows the meters performance to be validated for service on higher or lower viscosities and flow rates than the specified field operating conditions. In the example, all three product viscosities can be simulated with a 300 cSt test fluid by reducing the meter's maximum flow rate. As long as the ultrasonic meter is operating above its minimum specified flow rate, the test results are valid. Obviously, if higher viscosity fluids are available for testing, lower Reynolds Number testing can be achieved.

Table 2: Example of Flow Testing Conditions

Meter (Inches)	Flow Range			Viscosity (cSt)	Reynolds Number Range	
6	bph	560	1,690	300	690	2,080
	m3/h	90	270			
12	bph	1,900	5,710	300	1,170	3,510
	m3/h	300	910			
20	bph	4,200	12,600	300	1,550	4,650
	m^3/h	670	2,000			

For a wide dynamic operating range, multiple test systems as well as multiple test fluids may be required. Using multiple test systems is an accurate method of dynamic testing, as long as they use the same base standard. For large volume hydrocarbon test laboratories, this would be is a displacement or tank prover. The test systems should be accredited to a specific standard, typically ISO / IEC 17025. This provides the accuracy or expanded uncertainty on the certificate of accreditation which are factored into the test results (Addendum A). An example of dynamic testing results are shown in Figure 6. These results were obtained using the multiple systems and fluids approach in which a High Flow (HF) test system (Figure 7) and Multi-Viscosity (MV) test system (Figure 8) were used.

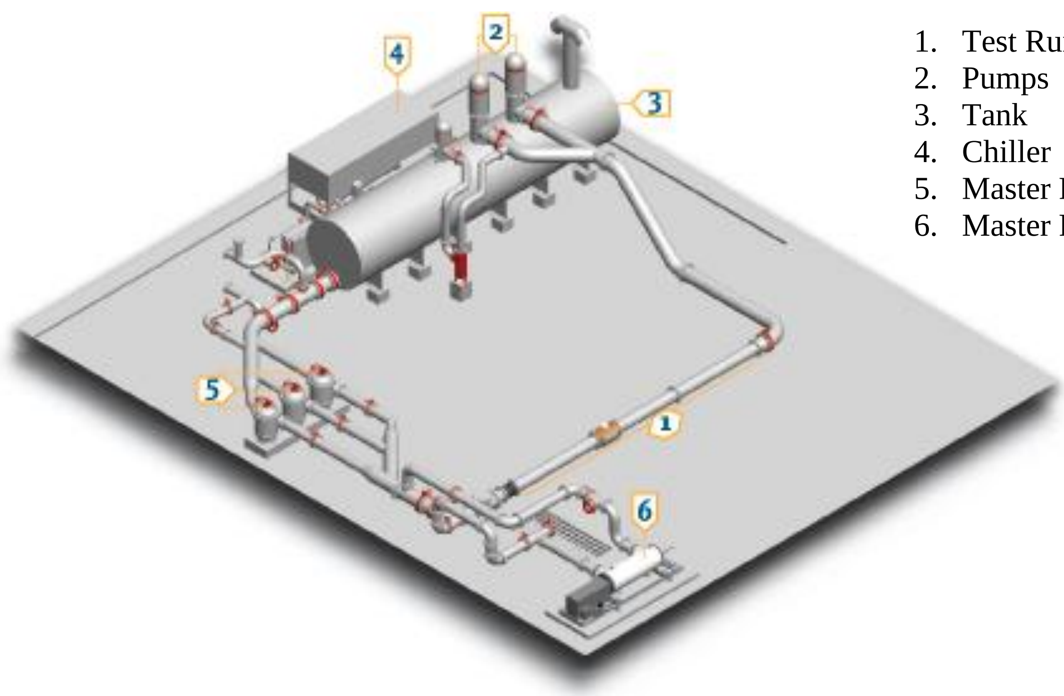


Reynolds Number Test

Size (Inches)	Test System		Flow (bph)		Viscosity		Reynolds Number	
			min	max	min	max	min	max
12	A	MV	1,900	8,000	18	300	1,170	82,000
	B	HF	6,330	19,000	10	18	64,880	350,550
Total Range			1,900	19,000	10	300	1,170	350,550

Figure 6: Multi-Viscosity Test System Dynamic Range

Dynamic similitude is achieved by replicating the Reynolds Number range. The testing can be accomplished by controlling flow rates and viscosities. Therefore the facility must have precise flow control and temperature stability in order to maintain the Reynolds Number throughout the testing. Temperature control is the largest contributing factor that determines how viscous of a fluid a test facility can handle. Heating and cooling systems which are necessary for temperature stability can be extremely large and costly. Therefore some manufacturers will utilize 3rd party test facilities to achieve the test range. Figures 7 and 8 are examples of two test systems. The main components are listed. Note that each test system is tied to the same standard, which in this case, is a Small Volume Master Prover (Item 6 in the Figures).



1. Test Run
2. Pumps
3. Tank
4. Chiller
5. Master PD Meter Provers
6. Master Prover

Figure 7: High Flow Test System

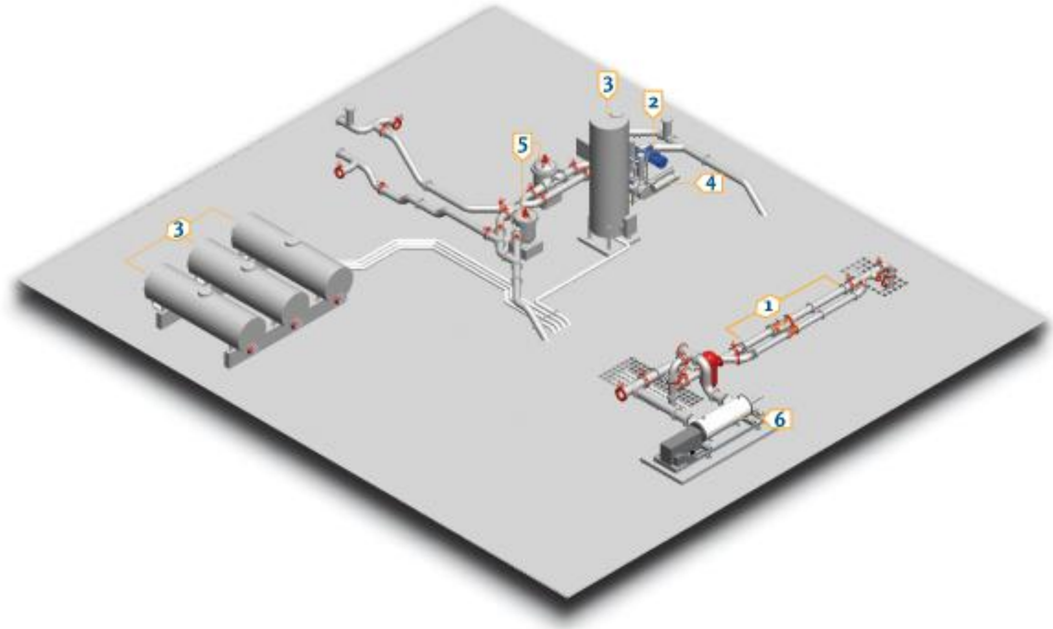


Figure 8: Multi-Viscosity Flow Test System

7. 12 INCH MULT-PATH DYNAMIC TEST

In this example, data is presented from a recent evaluation testing program for a major crude oil production company. The 12 inch multi-path ultrasonic meter was to measure a range of crude oils from 5 to 350 cSt and achieve a linearity of +/- 0.10% over the customer's flow range for a given crude oil. The operating conditions and Reynolds Number operating ranges are shown in Table 3.

Table 3: 12 inch Ultrasonic Customer Application Data

Meter Size	12
Meter Type	Multi-Path Ultrasonic
Flange Class	ASME Class 600
Meter Schedule (ID)	SCH XS (ID 11.750 inches)
Minimum Flow Rate	636 m^3/h [4,000 bph]
Maximum Flow Rate	1,113 m^3/h [7,000 bph]
Viscosity Range	5 –350 cSt
Reynolds Number Range	2,153 to 263,796

Table 4: 12 Inch Ultrasonic Dynamic Test Range

Meter Size	12
Meter Type	Multi-Path Ultrasonic
Flange Class	ASME Class 600
Meter Schedule (ID)	SCH XS ID (11.750 inches)
Minimum Flow Rate	79 m^3/h [500 bph]
Maximum Flow Rate	3,021 m^3/h [19,000 bph]
Viscosity Range	12 – 150 cSt
Reynolds Number Range (±10%)	1,884 to 298,340

Based on the on the field operating conditions and the flow test facility's capability, an equivalent dynamic test range is defined in Table 4. Utilizing the dynamic range, a detailed test plan was developed in which multiple test systems and products were used (Tables 5 and 6). The factory test plan thus covers the complete field measurement range.

Table 5: Dynamic Similitude Test 1

Test ❶						
Test System	High Flow (HF) Test Stand ***(Reference Addendum A)***					
PD Meter Master Prove	9.7 m^3 [61 bbl] Prove Volume					
Test Fluid	Medium Fluid					
Temperature	~32.2°C [90°F]					
Viscosity	12 cSt					
Nominal Flow Rates (BPH)	500	4,200	7,900	11,600	15,300	19,000
Nominal Flow Rates (M^3/HR)	79	668	1,256	1,844	2,433	3,020
Reynolds Number Test Range	7,851	65,949	124,047	182,145	240,243	298,340
Uncertainty	0.027% @ 0.95(normal) per API 5.8					

Table 6: Dynamic Similitude Test 2

Test ❷				
Test System	Multi-Viscosity (MV) Test Stand ***(Reference Addendum A)***			
PD Meter Master Prove	9.7 m^3 [61 bbl] Prove Volume			
Test Fluid	Extra Heavy Fluid			
Temperature	~35°C [95°F]			
Viscosity	150 cSt			
Nominal Flow Rates (BPH)	1,500	4,750	8,000	
Nominal Flow Rates (M^3/HR)	238	755	1,272	
Reynolds Number Test Range	1,884	5,967	10,049	
Uncertainty	0.027% @ 0.95(normal) per API 5.8			

The meter was then tested to determine the raw or uncompensated performance that covered a Reynolds Number range of 1,000 to 350,000 which is a much larger measurement range. The purpose for this was such that the correction method developed for a particular meter size and model can then be used in future applications that are covered within the Reynolds Number range. Due to the extensive testing on multiple products and test points, this approach helps in the manufacturing optimization. The test results for the larger range are shown in Figure 9. The uncorrected K-Factor variation was within +/- 1.113 %.

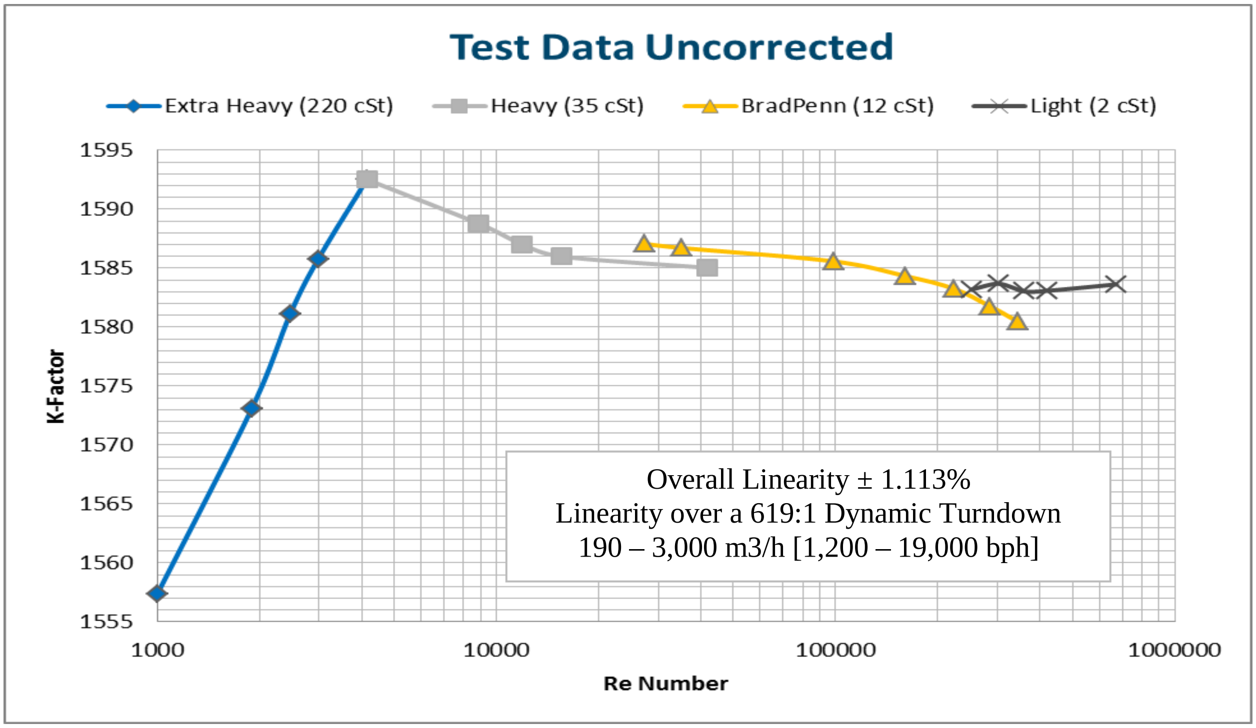


Figure 9: 12 Inch Ultrasonic Uncorrected Test Data

A linearization algorithm which reduces the meter sensitivity to flow profile and hence Reynolds Number changes is applied. From the empirical raw test data the algorithm was developed to compensate for the K-Factor variation due to viscosity effects on the meter's performance. The meter, when retested with the VPC algorithm in place, had a K-Factor variation of +/- 0.139% over this much larger dynamic range (Figure 10).

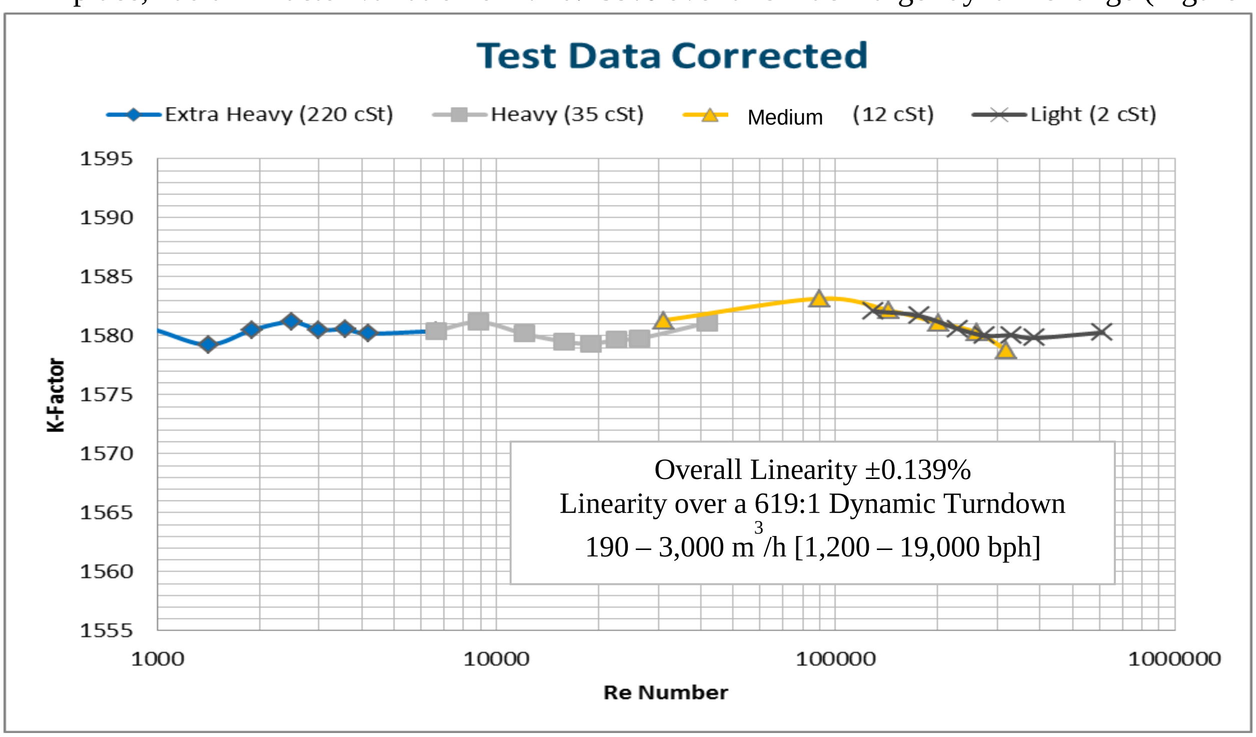


Figure 10: 12 Inch Ultrasonic Test Data with Correction

With the algorithm in place, a customer application can be tested over their specific dynamic range. The results of the two test plan (Tables 5 and 6) are shown in Figure 11.

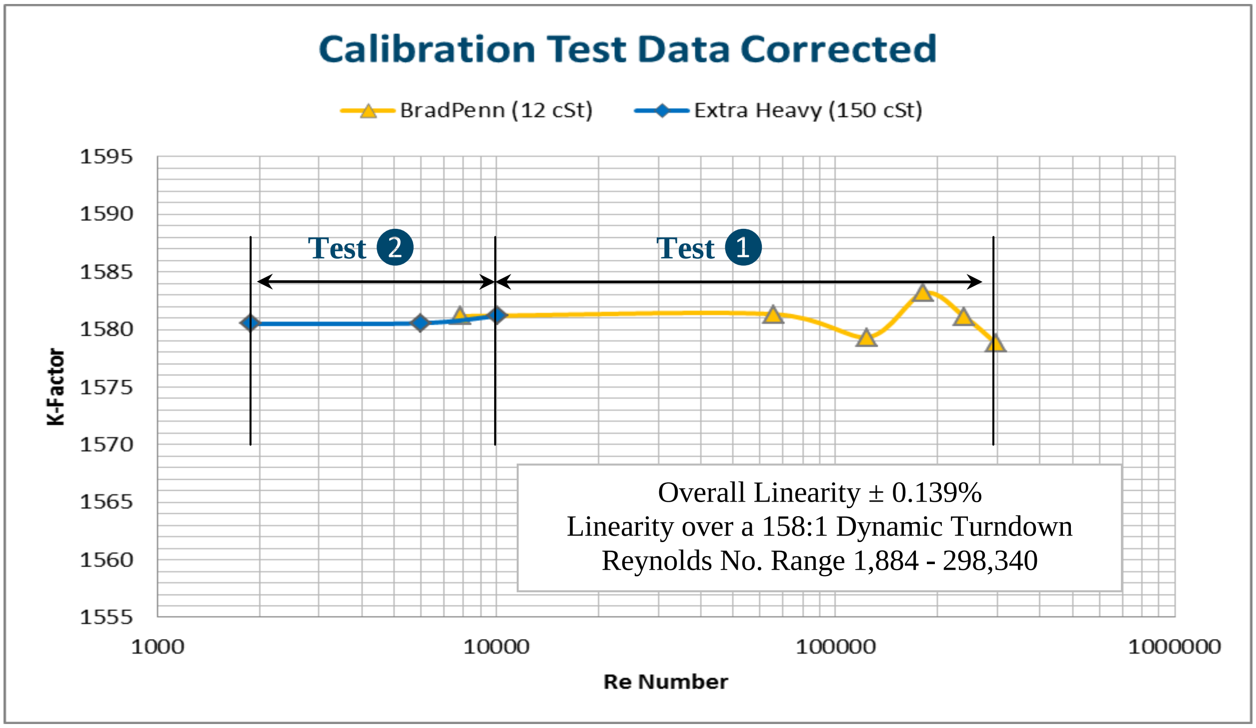


Figure 11: 12 Inch Ultrasonic Test Data with Correction

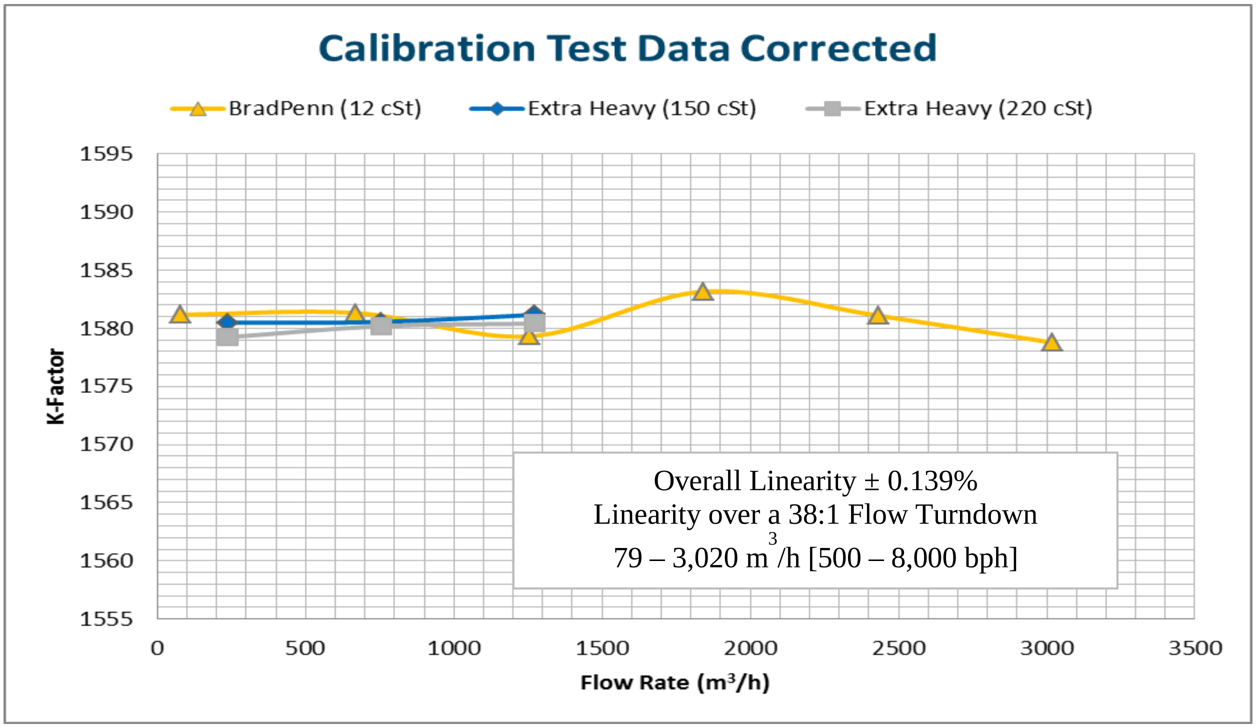


Figure 12: 12 Inch Ultrasonic Test Data with Correction

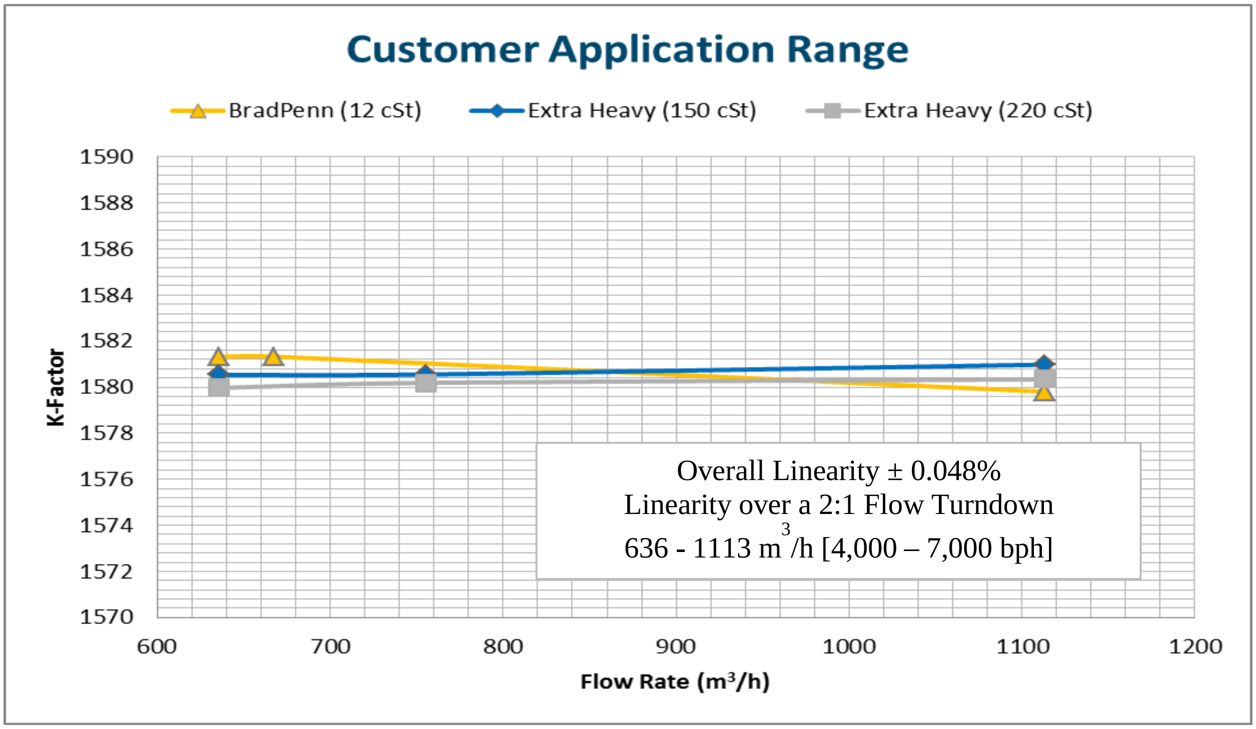


Figure 13: 12 Inch Ultrasonic Test Data with Correction within Customer Application Range

Representatives from the oil company witnessed the compensated meter performance over the complete dynamic operating range as outlined in the factory test program. The combined test results of K-Factor vs. flow rate are shown in Figure 13 which correlates to the Reynolds Number curve over a smaller range of the customer application. While the two product tests would have covered the customer range, an additional test was conducted up to 220 cSt to verify the reduced sensitivity in K-Factor variation compared to the other test fluids.

8. CONCLUSION

Liquid Ultrasonic Flow Meters (LUFM's) have gained acceptance in the petroleum industry for a wide range of applications. Initially they were used for non-custody applications of light hydrocarbons. But with advances in microprocessor, transducer, and electronic technology multi-path LUFM's can provide highly accurate flow measurement of crude oils from light condensates with a viscosity of less than 0.5 cSt to heavy crude oils over 2,000 cSt.

Developing and verifying the performance of these meters over field operating conditions is an essential part of the manufacturing process. It is especially important for high viscosity fluids where velocity profile correction is required to provide accurate and linear measurement. The key parameters that determine meter performance are size, flow rate, and viscosity, which are related by a well-established dynamic parameter - Reynolds Number.

By employing the principle of Dynamic Similitude, performance can be validated for service on a higher or lower viscosity than the test fluid. Simply stated, performance at a given Reynolds Number is the same no matter the combination of flow rate and viscosity. Therefore by utilizing multi-viscosity test systems, Dynamic Tests can be run to determine measurement accuracy over a wide range of operating conditions.

References

[1] **API MPMS Ch. 5.8**, "Manual of Petroleum Measurement Standards, Chapter 5.8 – Measurement of Liquid Hydrocarbons by Ultrasonic Flow Meters", 2nd Edition, November 2011.

[2] **ISO 12242:2012**, "Measurement of fluid flow in closed conduits – Ultrasonic transit-time meters for liquid, First edition 2012-07-01

[3] **Lunde, P., Kalivoda, R.J.** , "Liquid Ultrasonic Flow Meters For Crude Oil Measurement", 23rd International North Sea Flow Measurement Workshop, Tonsberg, Norway, 18-21 October 2005.

Addendum A

Test Facility Expanded Uncertainty

Test Facility: FMC Technologies Flow Research and Test Center, Erie, PA USA

Meter Types: Positive Displacement, Helical and Conventional Turbine, and Ultrasonic

Test System[1]	Viscosity Range (cSt)		Flow Rate (m^3/h)		Flow Rate (bph)		Prove Method[2]	Expanded Uncertainty[3]
	min	max	min	max	min	max		
HF	10	25	30	135	190	850	DPM	0.075%
			135	2,782	850	17,500		0.045%
			60	158	380	995	MMPM	0.120%
			158	6,680	995	42,000		0.084%
MV	2	150	30	135	190	850	DPM	0.065%
			135	1,270	850	8,000		0.047%
			60	103	380	650	MMPM	0.091%
			103	1,270	650	8,000		0.084%
	150	250	30	135	190	850	DPM	0.055%
			135	1,270	850	8,000		0.042%
LF	2	6	0.6	270	4	1,700	DPM	0.037%
			4.0		25		MMPM	0.077%
	7	25	0.6		4		DPM	0.036%
			3.2		20		MMPM	0.076%
	20	100	0.6		4		DPM	0.035%
			2.4		15		MMPM	0.075%
	80	225	0.6		4		DPM	0.035%
			1.6		10		MMPM	0.075%

Notes:

1.) HF (High Flow); MV (Multi-Viscosity); LF (Low Flow)

2.) DPM (Direct Proving Method with Small Volume Prover); MMPM (Master Meter Proving Method with PD Meters)

3.) Expanded uncertainty based on a coverage factor of, $k = 2$, with a level of confidence of approximately 95%.