Reynolds Number Meter Proving

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Industry Measurement Group Presentation

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Reynolds Number Meter Proving

Topics

- ☐ What is Reynolds Number
- ☐ Reynolds Number and the Turbine Meter
- ☐ Reynolds Number Meter Proving
- ☐ The FortisBC Triple Point Meter Proving Facility
- ☐ Questions

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Dimensionless Quantity

A dimensionless quantity is a number which has no association with any physical dimensions …….

Dimensionless Quantity

Examples of dimensionless quantities:

Name	Symbol	Description
Specific gravity	SG	ratio of density of a substance to a reference substance
Pi	π	ratio of a circle's circumference to its diameter
Q factor	Q	damping of oscillator or resonator, energy stored vs energy lost
Gain	G	signal output to signal input ratio
Mach number	M	Ratio of speed of an object moving through a fluid and the local speed of sound
Reynolds number	Re	ratio of fluid inertial and viscous forces

Dimensionless Quantity

For example:

$$\text{Mach Number } M = \frac{V_{\text{object}}}{V_{\text{sound}}}$$

M is independent of the units used in the velocities, as long as the two velocities have the same units.

Buckingham Pi Theorem

No, it is a different kind of pi !

Buckingham Pi (π) Theorem

The Buckingham Pi Theorem was named after an American physicist Edgar Buckingham for his work in fluid mechanics in 1914.

It states that any physical law can be expressed as an identity involving only dimensionless combinations (ratios or products) of the variables linked by the law.

The Buckingham π Theorem proves the general method for Dimensional Analysis.

Reynolds Number is a good example of such dimensionless number

Osborne Reynolds (1842-1912)

Osborne Reynolds at age 24 (1866)

- Osborne Reynolds was a British physicist and engineer.
- His most notable work was in fluid dynamics – conditions in which fluid flow in pipes transitioned from laminar flow to turbulent flow.
- Reynolds number (Re), is a dimensionless quantity that is used to predict similar flow patterns under different fluid flow conditions. It is named after Osborne Reynolds.

Reynolds Number

$$\text{Reynolds Number} = \frac{\overbrace{\rho v D}^{\text{Inertial Forces}}}{\underbrace{\mu}_{\text{Viscous Forces}}}$$

ρ = fluid density

v = flow velocity

D = characteristic dimension

μ = dynamic viscosity

Dimensional Analysis of Reynolds Number

$$\text{Reynolds Number} = \frac{\rho v D}{\mu}$$

ρ = fluid density kg·m^{-3}

v = flow velocity m·sec^{-1}

D = characteristic dimension m

μ = dynamic viscosity poise = Pa·s = kg·m^{-1}·sec^{-1}

Dimensional Analysis of Reynolds Number

$$\text{Reynolds Number} = \frac{\rho v D}{\mu}$$

$$\text{Re} = \frac{\cancel{\text{kg}}\cdot\cancel{\text{m}}^{-3} \quad \cancel{\text{m}}\cdot\cancel{\text{sec}}^{-1} \quad \cancel{\text{m}}}{\cancel{\text{kg}}\cdot\cancel{\text{m}}^{-1}\cdot\cancel{\text{sec}}^{-1}}$$

Reynolds Number is a “Dimensionless Quantity”

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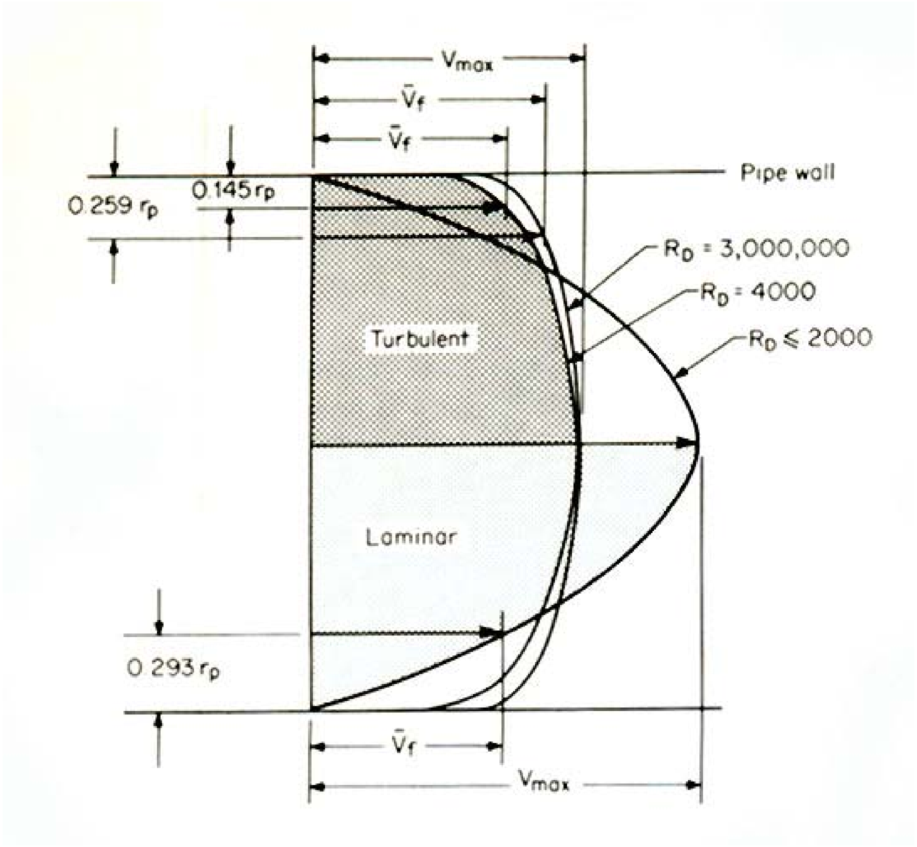
Flow Profiles at Various Reynolds Number



Velocity Profiles in Laminar and Turbulent Pipe Flow

Laminar if Re < 2000

Transient if 2000 < Re < 4000

Turbulent if Re > 4000

Reynolds Number examples:

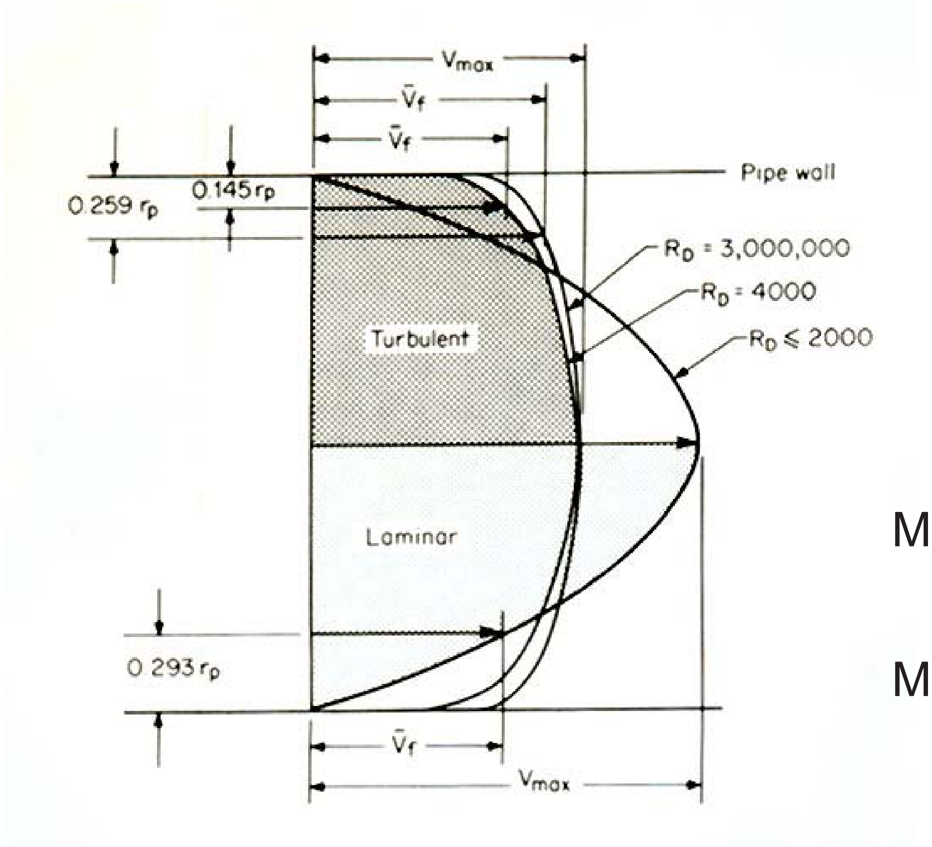
12" Standard Capacity Turbine Meter at 350 psia

at 10% of capacity Re = 700,000

at 95% of capacity Re = 6,800,000

Flow Measurement Engineering Handbook – R.W. Miller, McGraw-Hill

Flow Profiles at Various Reynolds Number



Velocity Profiles in Laminar and Turbulent Pipe Flow

$$\text{Re} = \frac{\rho v D}{\mu}$$

More inertial forces → more turbulent flow

More viscous forces → more orderly flow

Flow Measurement Engineering Handbook – R.W. Miller, McGraw-Hill

Visible Reynolds Number ?

Reynolds Number can be observed
in everyday life….

Dynamic Similarity

- Dynamic Similarity describes the relationship between two fluid flows having identical types of forces that are parallel at all corresponding points, with magnitudes related by a constant scale factor.

- Dynamic Similarity can be achieved by matching the Reynolds number of two fluid flows.

Dynamic Similarity and Reynolds Number

- The theory of dynamic similarity stipulates that the same object when exposed to a flow with the same Reynolds number would behave the same way.
- Dynamic similarity makes it possible to scale results from model tests to predict corresponding results for the full-scale prototype.

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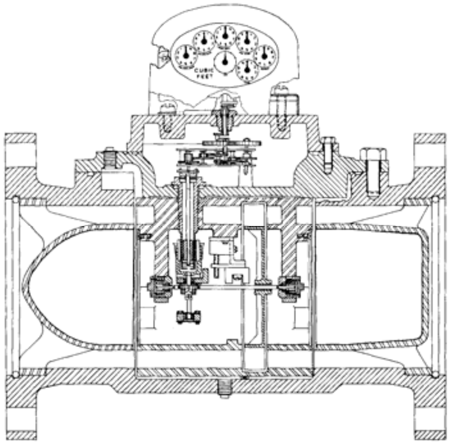
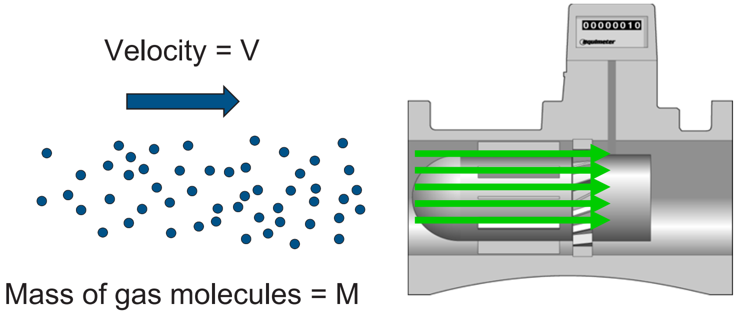
How does turbine meter work ?



The Law of Conservation of Energy

Kinetic Energy = Dynamic Energy of Mass in Motion



$$KE = {}^{1}/_{2}\, M\, V^2$$

Where: KE = Kinetic energy of the moving gas molecules
M = Mass of gas molecules
V = Velocity of gas molecules

In an turbine meter, a portion of the linear kinetic energy of the moving gas molecules is converted into rotational energy of the rotor

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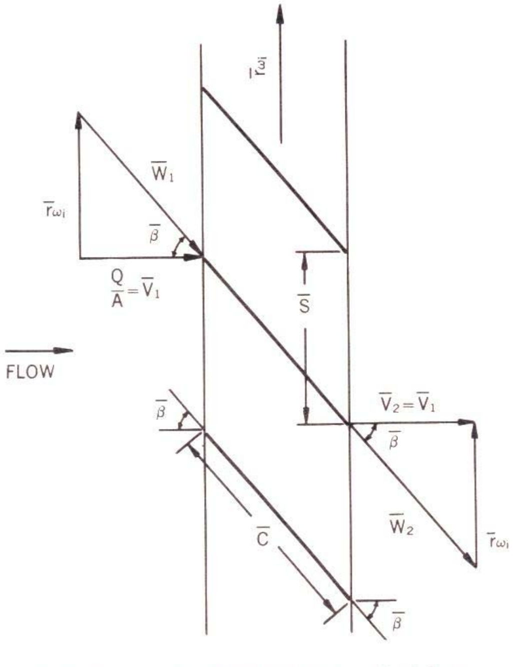
Principle of Turbine Meters

Analysis of an Ideal Rotor



Velocity Diagram For Rotor Radius ($\bar{r}$)—Ideal Case.

$\bar{r}$	is the average of the rotor radius
Q	is the volume flow rate
A	is the annular flow area
$\bar{\beta}$	is the blade angle
V_1, V_2	are the gas velocities at point (1) and (2)
ω_1, ω_2	is the fluid velocity relative to the rotor blades
ω_i	is the ideal angular velocity

$$\frac{\omega_i}{Q} = \frac{\tan\bar{\beta}}{\bar{r}A} \qquad \text{——— (1)}$$

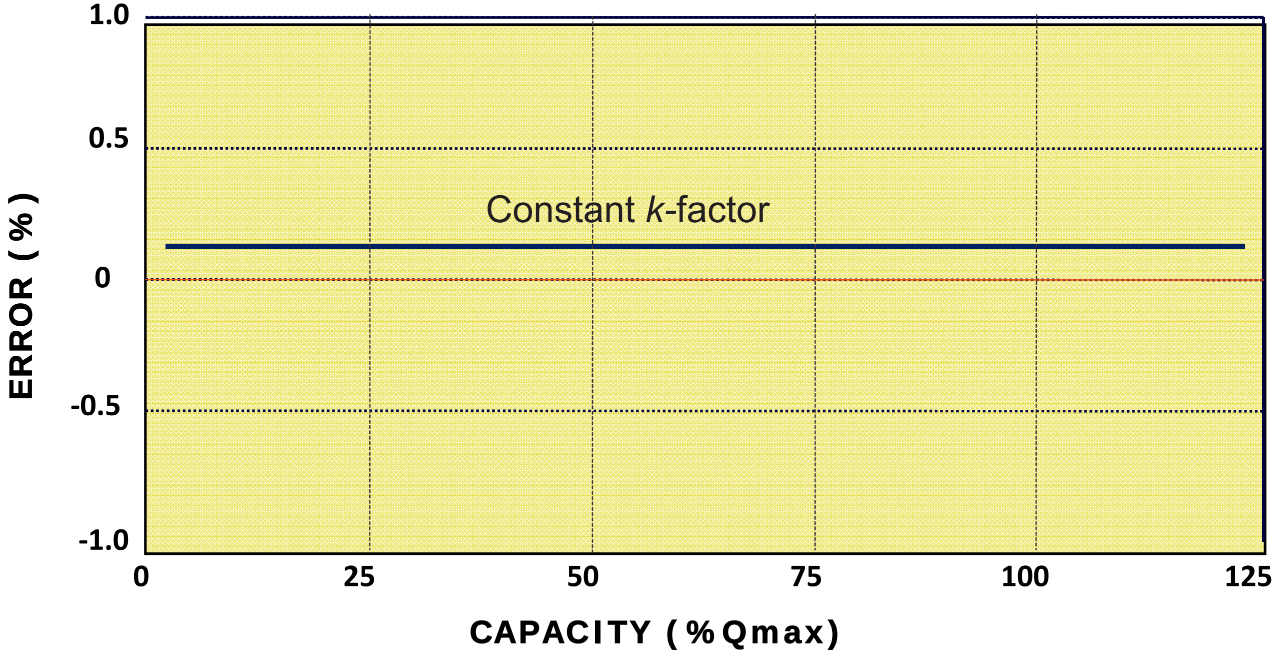
$$Q = \frac{\bar{r}A\omega_i}{\tan\bar{\beta}} \qquad \text{——— (2)}$$

The angular velocity of the rotor is proportional to the volume flow rate

$$\boxed{Q \propto \omega_i} \qquad \text{——— (3)}$$

Material quoted in part from Sensus publication

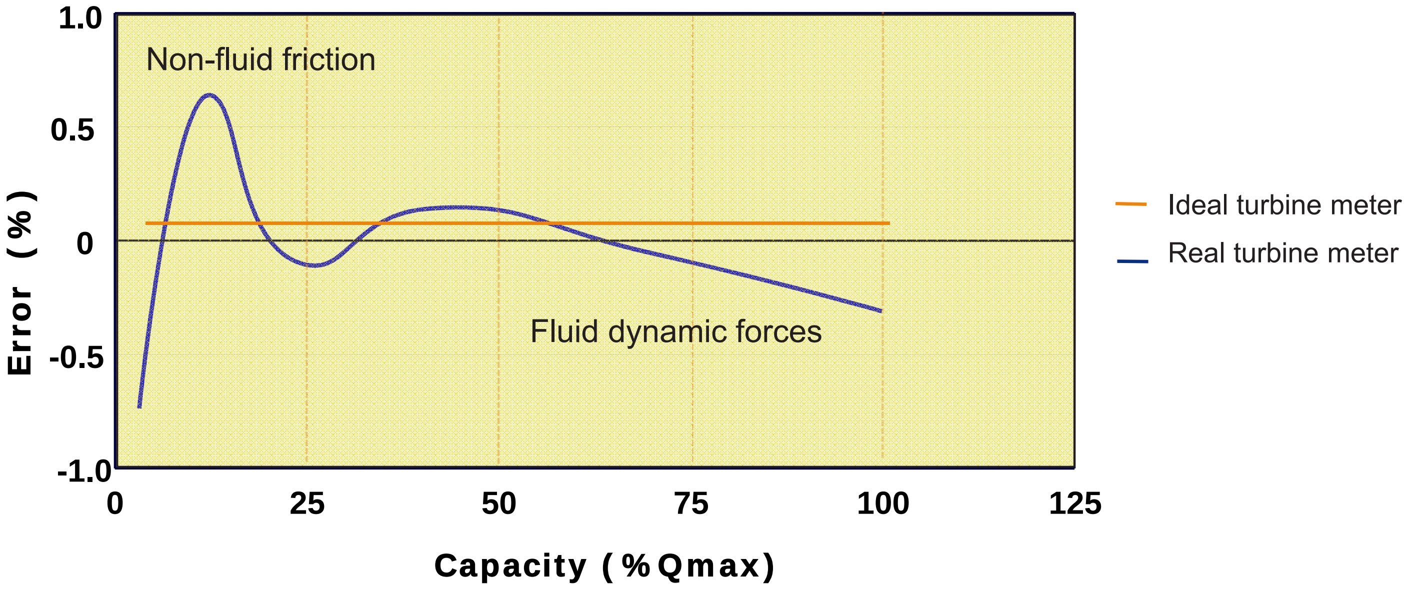
Performance Curve of an "Ideal" Gas Turbine Meter



An ideal turbine meter has a single *k*-factor and a flat error curve extending from Q_{min} to Q_{max}

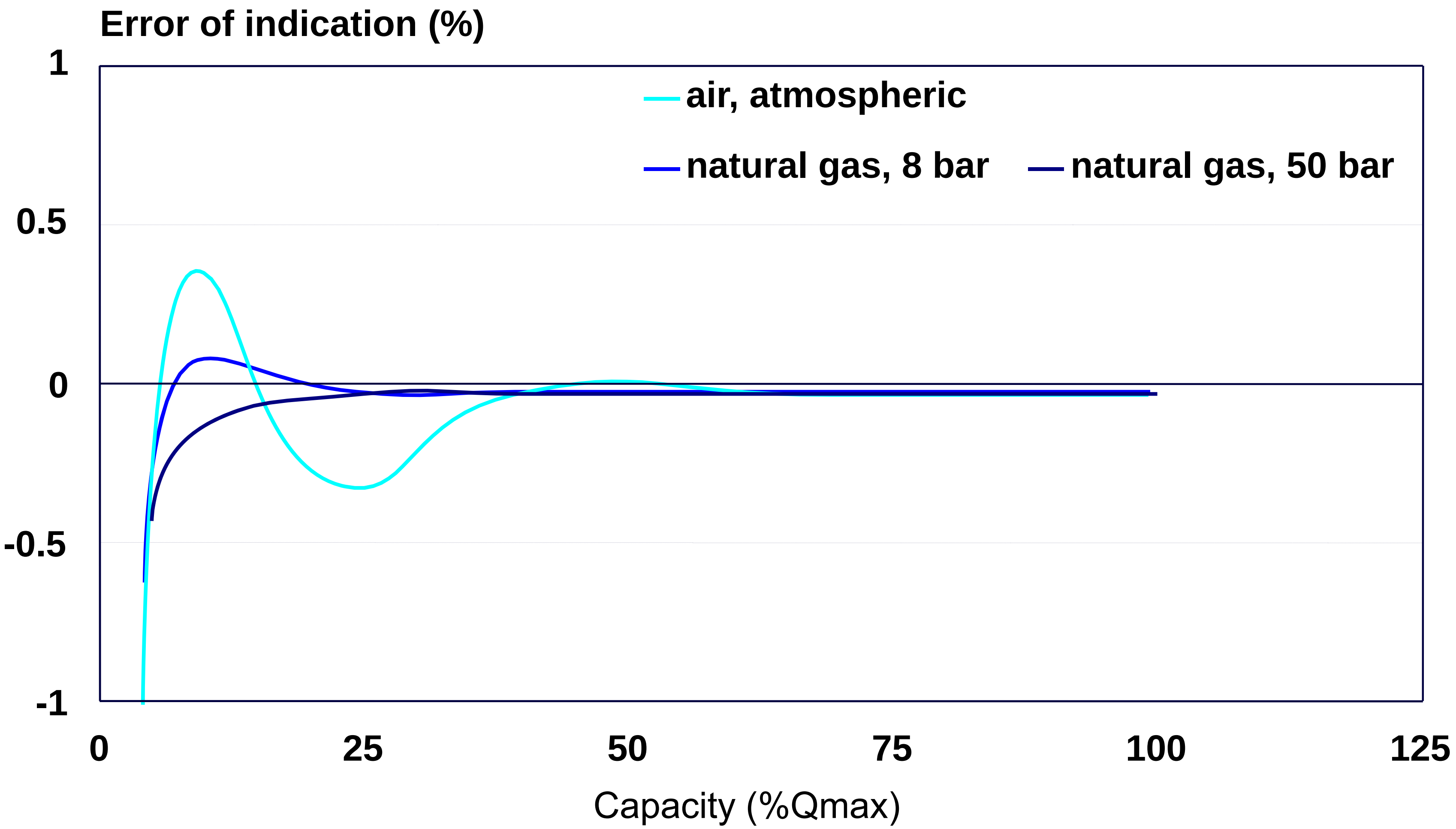
Non-ideal Turbine Meter Characteristics

Of course nothing is perfect:



Performance curve of a “real” gas turbine meter

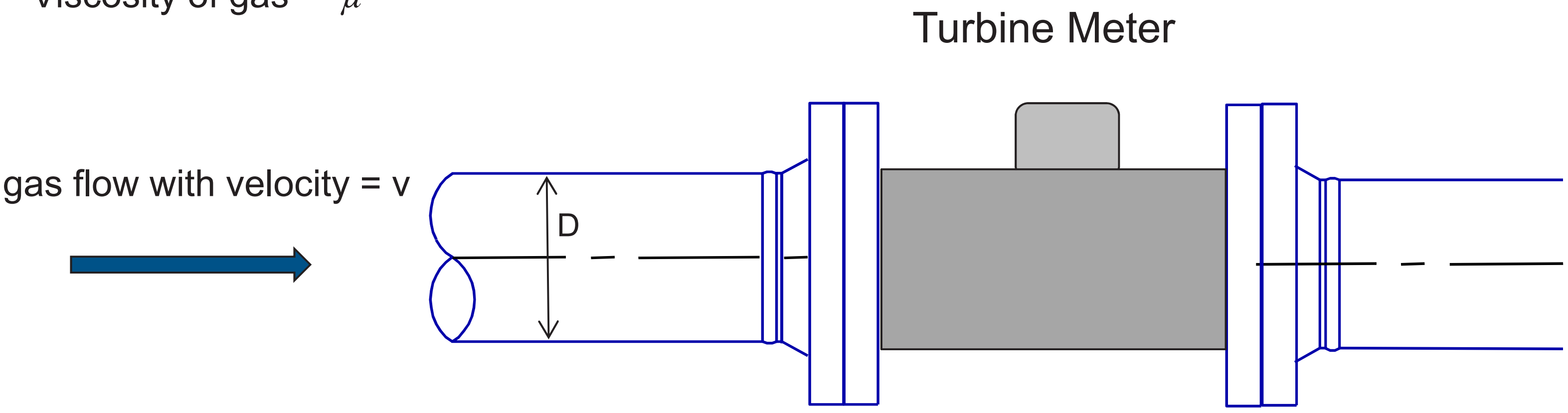
Turbine Meter Error Performance vs Flow Rate



Typical Turbine Meter Performance vs Flow Capacity

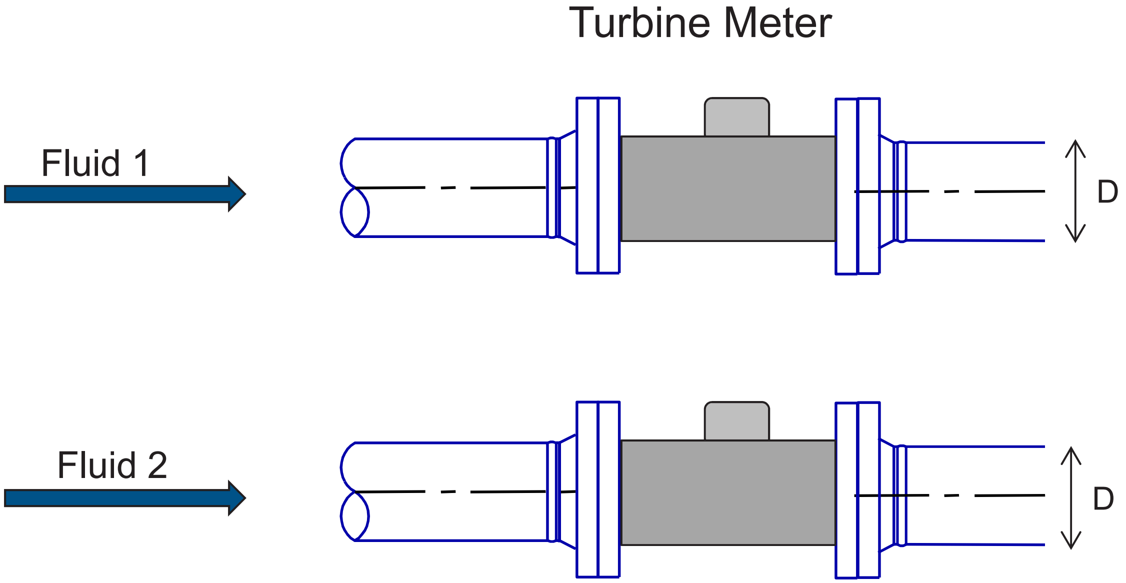
Pipe Flow Reynolds Number

Characteristic Dimension = Pipe diameter D
Density of gas = ρ
Viscosity of gas = μ



Pipe flow Reynolds number = $\frac{\rho v D}{\mu}$

Pipe Flow Reynolds Number



$$\text{Pipe flow Reynolds number} = \frac{\rho_1 v_1 D}{\mu_1} = \frac{\rho_2 v_2 D}{\mu_2}$$

Based on the theory of Dynamic Similarity, a turbine meter is expected to behave in the same way even when it is exposed to a different fluid if the Reynolds number of the two flows are identical.

Reynolds Number

Studies conducted at SwRI* and CEESI * demonstrated that the calibration factors of commercially available gas turbine meters are significantly affected by the Reynolds numbers of the flow.

References:

(1) Effects of Line Pressure and Density of Turbine Meter Measurement Accuracy Between 30 and 700 psig in Natural Gas, GRI-03/0050, July 2003;

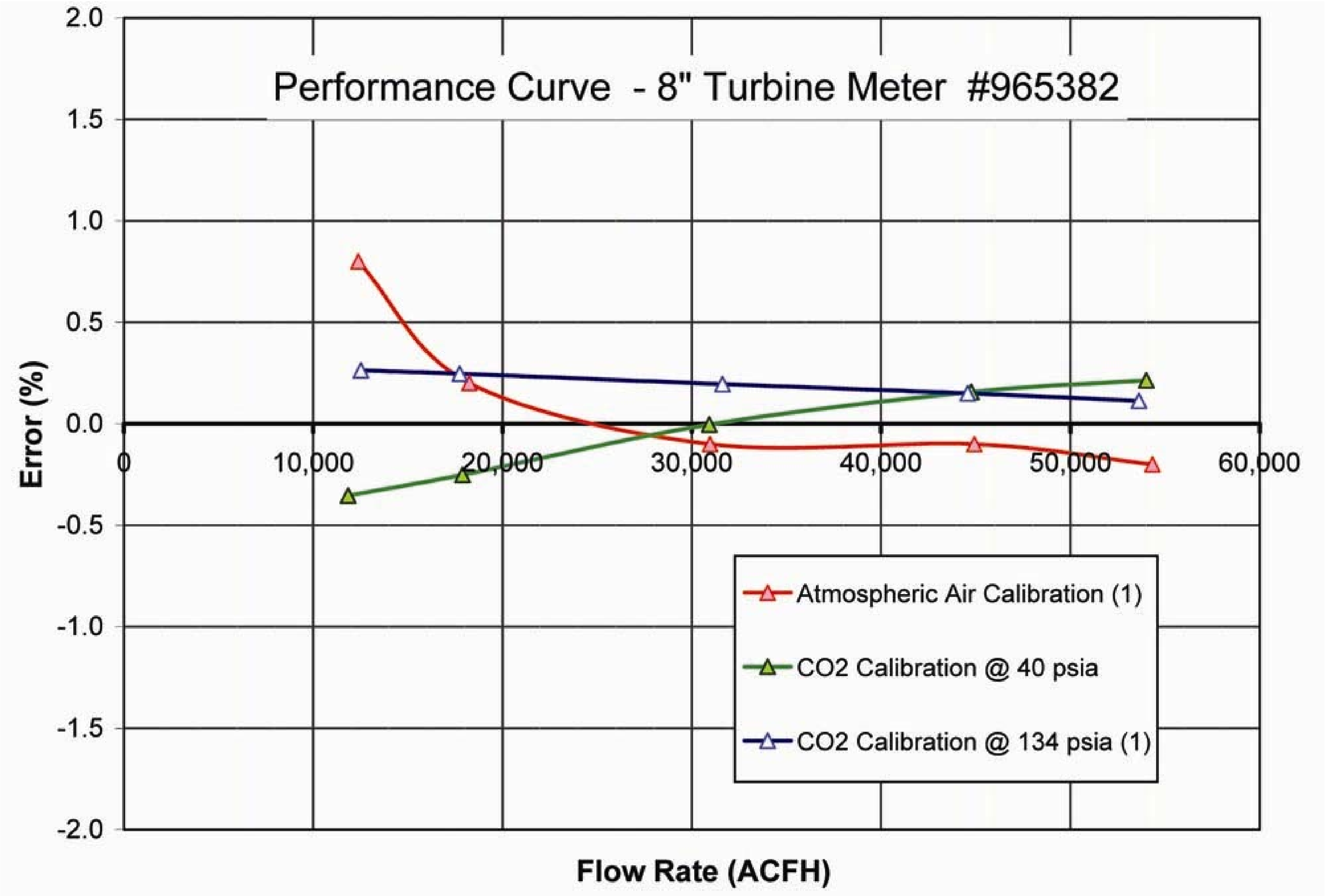
(2) Effects of Line Pressure and Density of Turbine Meter Measurement Accuracy at Conditions from Atmospheric Air to 700 psig Natural Gas, GRI-03/00172, August 2004;

(3) Measurement of Natural Gas by Turbine Meters, 3rd revision published by AGA, February 2006.

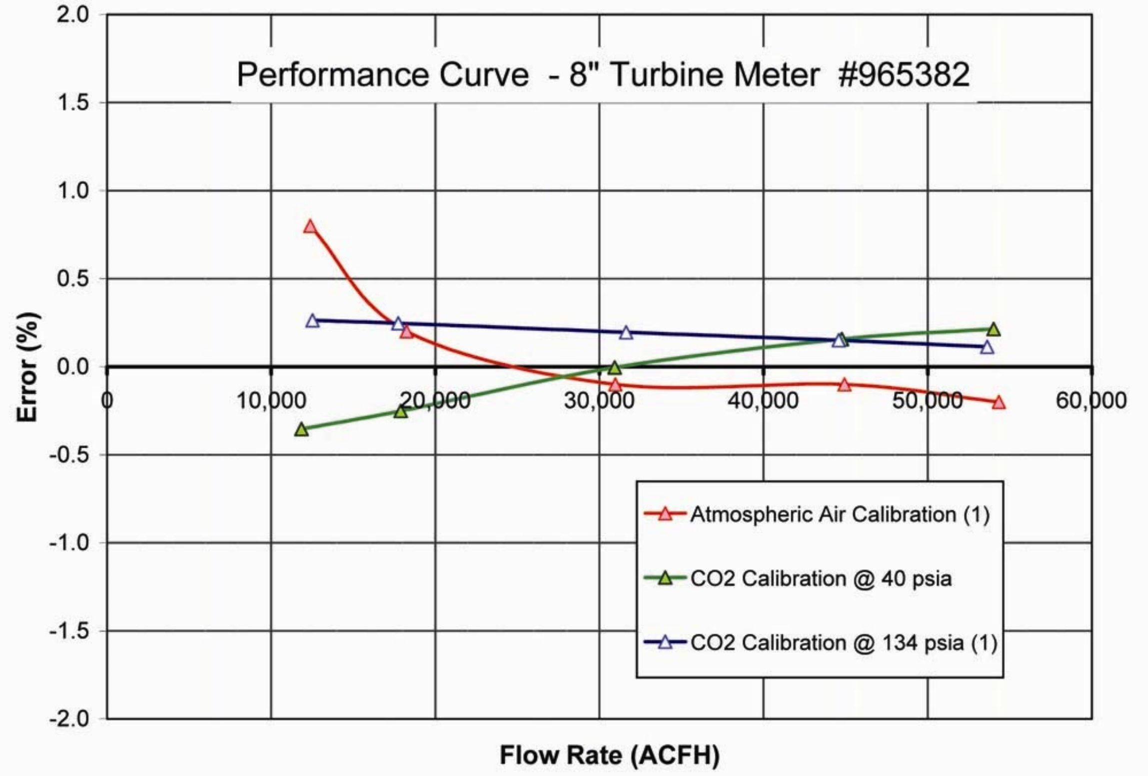
Reynolds Number Effect on Turbine Meters

What does that mean in terms of meter performance?

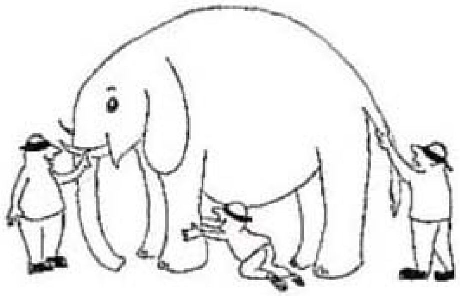
Pressure Effect on a Turbine Meter



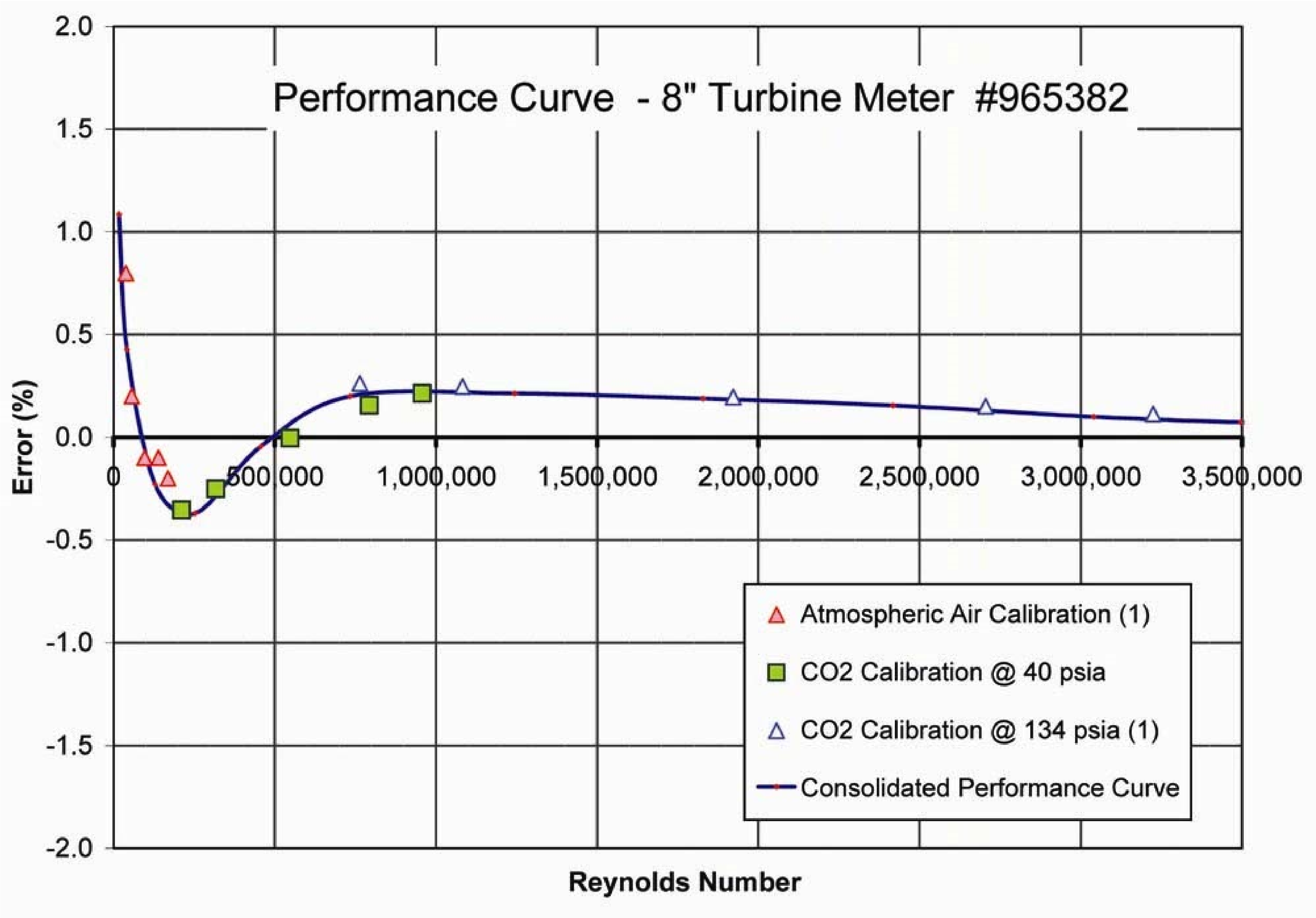
Pressure Effect on a Turbine Meter



- ☐ Each one of these three curves has very distinct and different attributes.
- ☐ Any one of these three calibration curves does not represent the behavior of the meter operating under the other two sets of conditions.



Performance Curve Expressed in Reynolds number

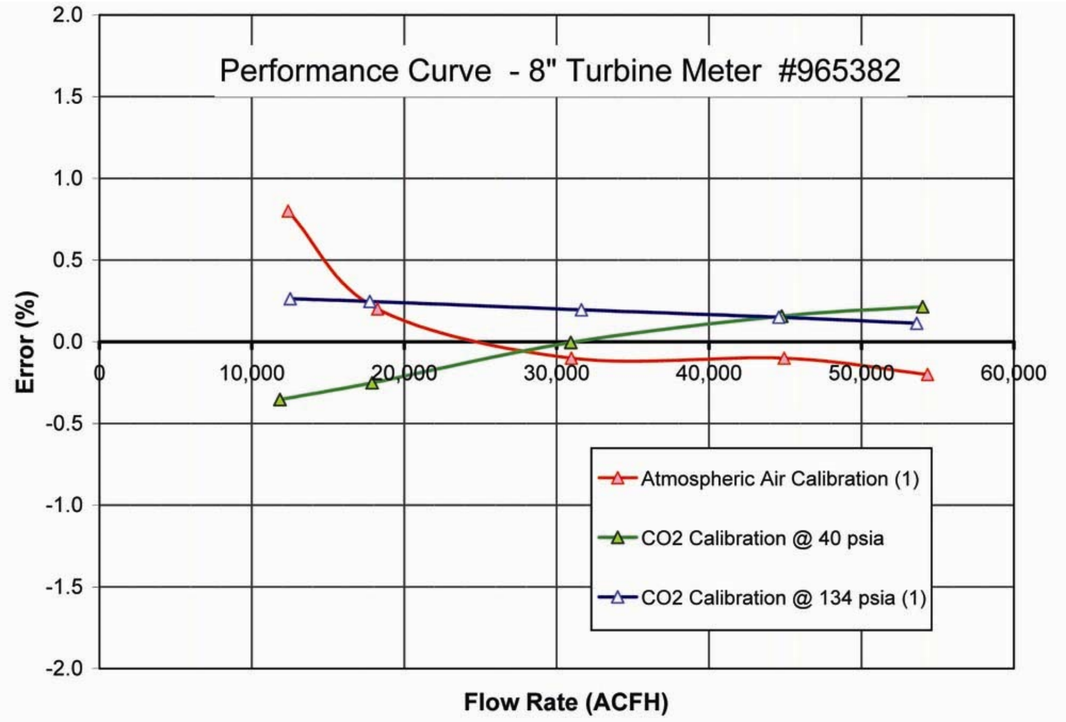


Reynolds Number

The performance of turbine meters are closely related to Reynolds number

Turbine meters are essentially
Reynolds number machines !

Cost of Flow Measurement Error



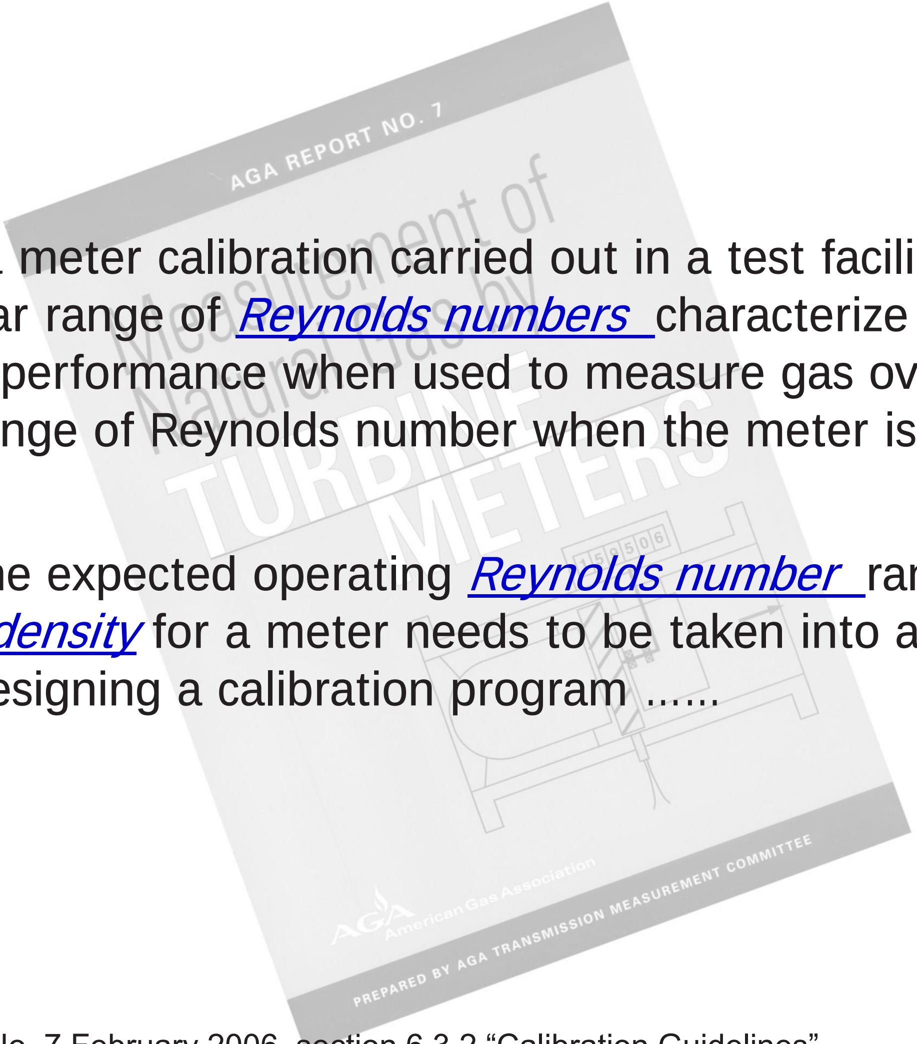
An 8-inch standard capacity turbine meter operating at 30% capacity on average at 500 psig for 6 years will cost the gas company or its customer $750,000 if the meter was calibrated in atmospheric air.

Note 1: Turbine meters operating at 30% of Qmax average

2. Energy content of natural gas based on 1.0205 MBtu/cu.ft.

3. Cost of energy calculated based on $4.00 USD per MMBtu

Recommendations in AGA-7 Report



...........a meter calibration carried out in a test facility over a particular range of *Reynolds numbers* characterize the meter's performance when used to measure gas over the same range of Reynolds number when the meter is in service

.... the expected operating *Reynolds number* range and/or *density* for a meter needs to be taken into account when designing a calibration program ......

Quote from AGA Report No. 7 February 2006, section 6.3.2 "Calibration Guidelines"

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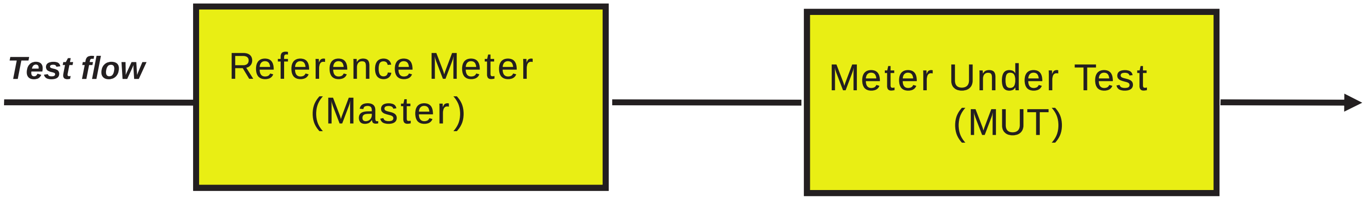
Turbine Meter Proving

Principle of Transfer Meter Provers

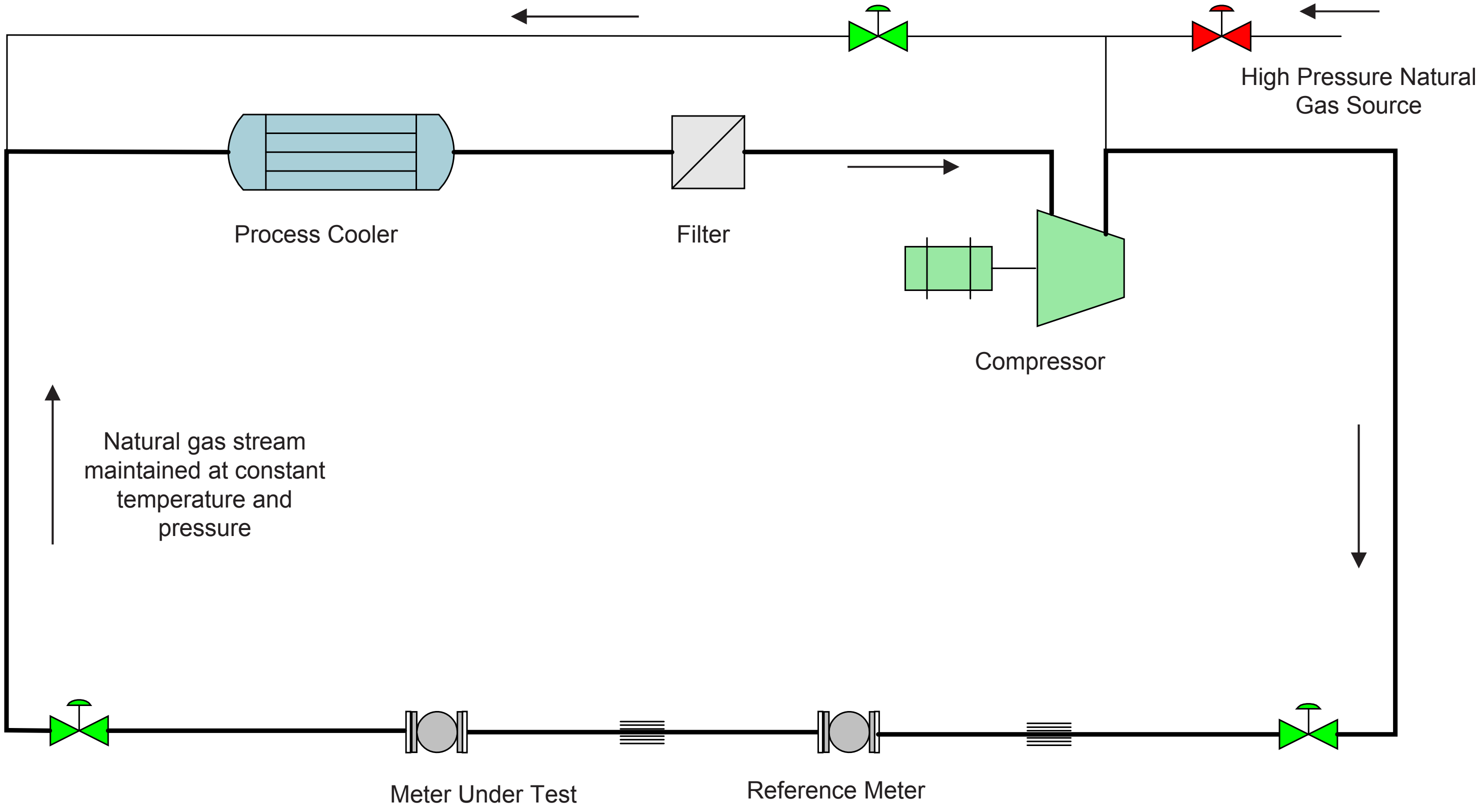


Comparing the volume throughput with a well known reference under the *same conditions*

↓

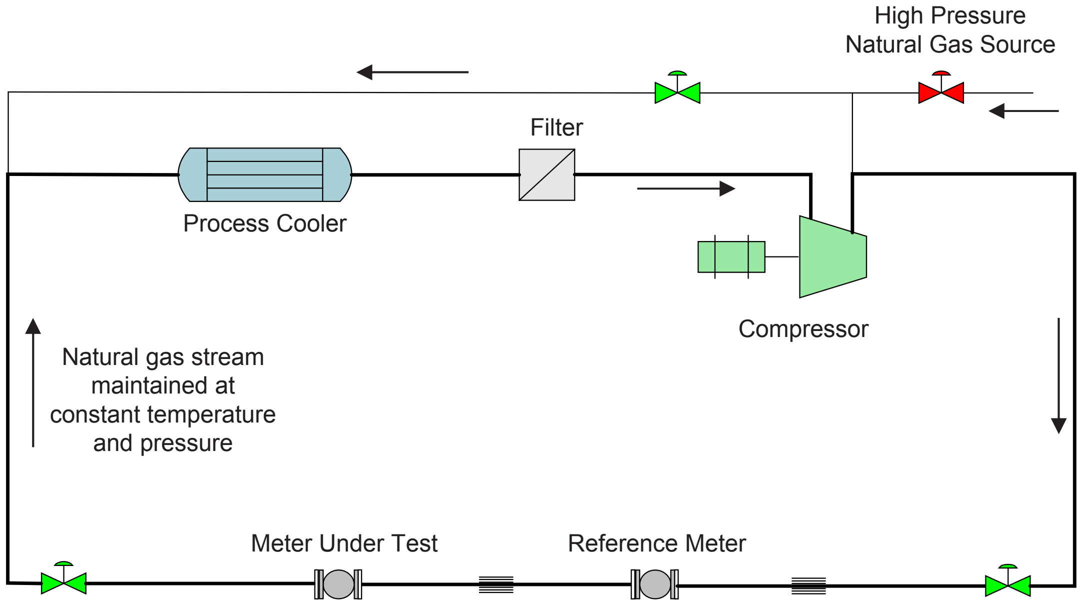
i.e. Testing or converting to the same pressure and temperature

A Conventional High Pressure Transfer Prover Loop



LAYOUT OF A TYPICAL CLOSE-LOOP HIGH PRESSURE METER PROVING FACILITY

A Conventional High Pressure Transfer Prover Loop



LAYOUT OF A TYPICAL CLOSE-LOOP HIGH PRESSURE METER PROVING FACILITY

Requirements:

- Proximity to high pressure natural gas pipeline
- Wide range of flow rate
- Ability to utilize “used” gas
- Ability to support flow rate year round

Locations suitable for building a conventional high pressure meter proving station are rare

Meter Calibration with Alternate Fluids

What about calibrating turbine meters with an alternate test fluid?

- Not a new idea, air has been used extensively for calibrating turbine meters for many years.
- Based on some of the earlier research work, it should be possible to get the same test result using an alternate gas if the Reynolds number is matched to field conditions.

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The Fortis BC Triple Point High Pressure Meter Calibration Facility

- Use of an alternate test medium other than natural gas to establish high Reynolds number flow.
- Use the same test medium as a cooling agent for the test loop.

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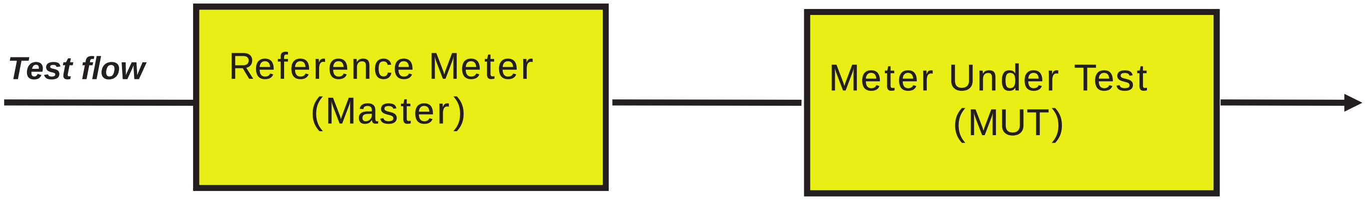
Advantages of using Carbon Dioxide Gas for Proving Turbine Meters



- Being non-combustible, carbon dioxide is safer to handle than natural gas at a test facility;
- Comparing to both natural gas and air, the lower operating pressures needed to reach the target meter test Reynolds number require less compression;
- The fact that the carbon dioxide meter proving loop can operate at a lower pressure means that time saving devices such as automated test meter clamps can be easily and inexpensively deployed;
- The triple point of carbon dioxide occurs much closer to ambient conditions than most gases, a property that allows the temperature of the flowing gas in the test loop to be controlled by direct injection of carbon dioxide in the liquid phase.

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Advantages of using Carbon Dioxide Gas for Proving Turbine Meters

Comparing CO_2 to Natural Gas:

$$\frac{R_{e(CO2)}}{R_{e(CH4)}} = \frac{\dfrac{G_{(CO2)}\ \rho_{(air)}\ v D}{\eta_{(CO2)}}}{\dfrac{G_{(CH4)}\ \rho_{(air)}\ v D}{\eta_{(CH4)}}} \qquad \text{……..(3)}$$

$$= \frac{G_{(CO2)}\ \eta_{(CH4)}}{\eta_{(CO2)}\ G_{(CH4)}}$$

$$\frac{R_{e(CO2)}}{R_{e(CH4)}} = 2.10 \qquad \text{……..(4)}$$

Effective Test Pressure (CO_2) = $\dfrac{R_{e(CO2)}}{R_{e(CH4)}} = 2.10$

Advantages of using Carbon Dioxide Gas for Proving Turbine Meters

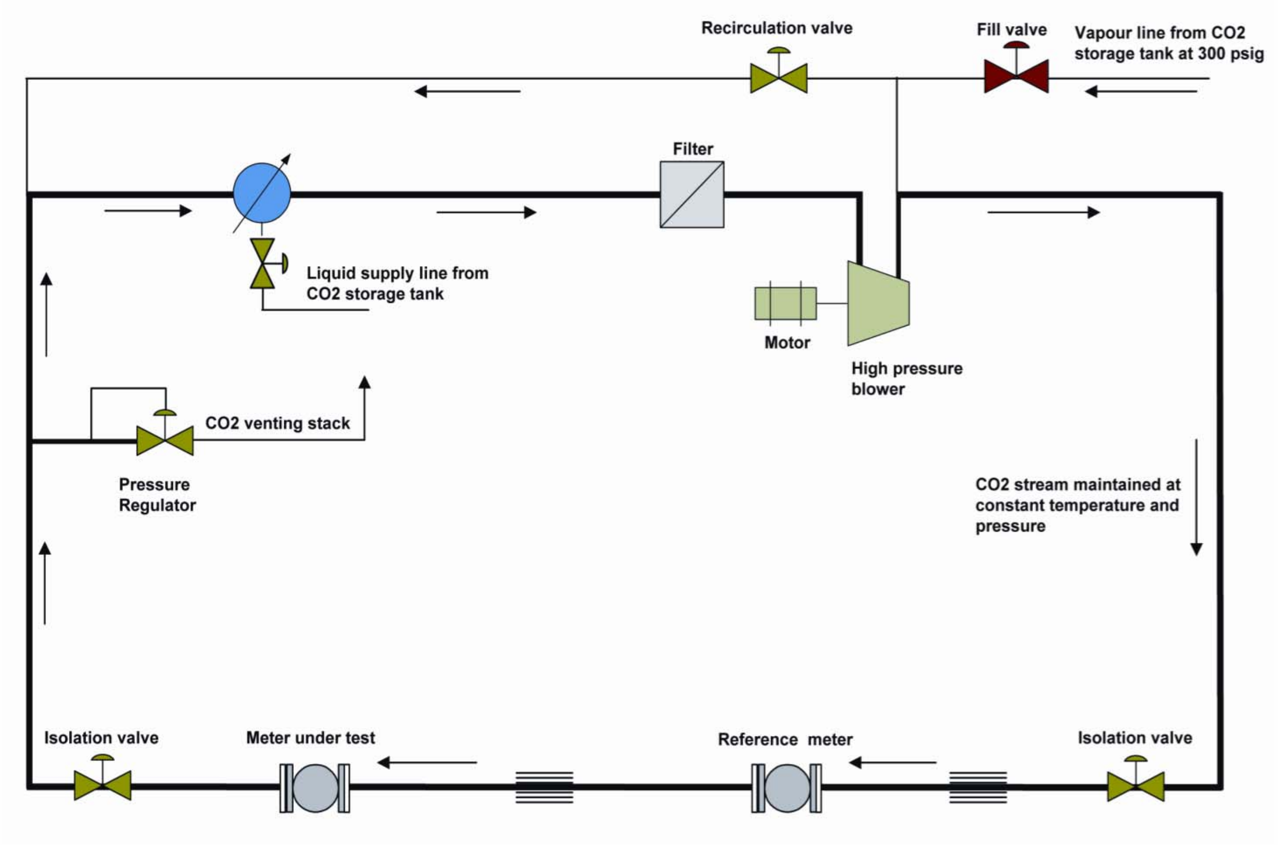
Comparing the Density of Air, Natural Gas, and Carbon Dioxide:

Similar considerations can be given to the density ratios of the gases used in the previous example. Comparing air with natural gas under the same operating conditions, the density ratio is 1.67. The carbon dioxide to natural gas density ratio is 2.75.

$$\frac{\rho_{(Air)}}{\rho_{(Natural\ gas)}} = 1.67 \qquad \text{........(5)}$$

$$\frac{\rho_{(CO2)}}{\rho_{(Natural\ gas)}} = 2.75 \qquad \text{........(6)}$$

CO_2 High Pressure Prover Loop



This prover loop is just like any conventional high pressure test loop, but with the following two exceptions:

A. The test medium is carbon dioxide;

B. The cooling agent is liquefied carbon dioxide.

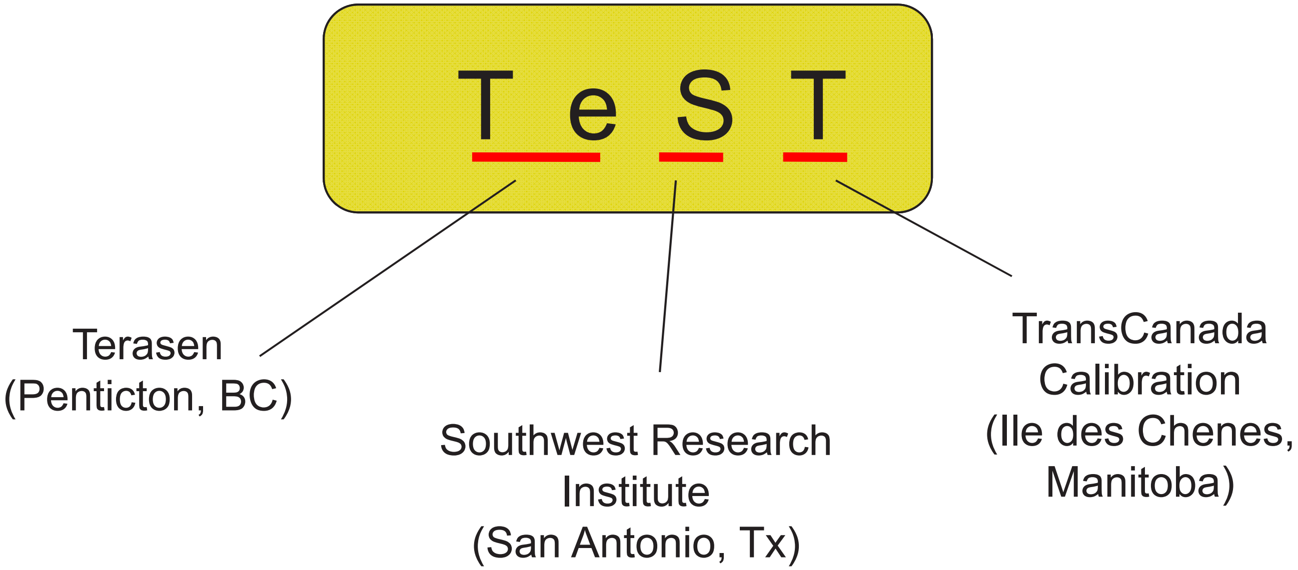
Fortis BC Triple Point Test Facility's performance standards:

- ☐ ISO 17025 Approval
- ☐ Recognized by Measurement Canada under Bulletin G-16
- ☐ Measurement traceable to NMI (Dutch) and Pigsar (German)
- ☐ Routine intercomparison with SwRI (NIST) and TCC (Canada)

Inter-Comparison Program

Comparison of test facilities

TeST is a interfacility measurement quality assurance program



T e S T

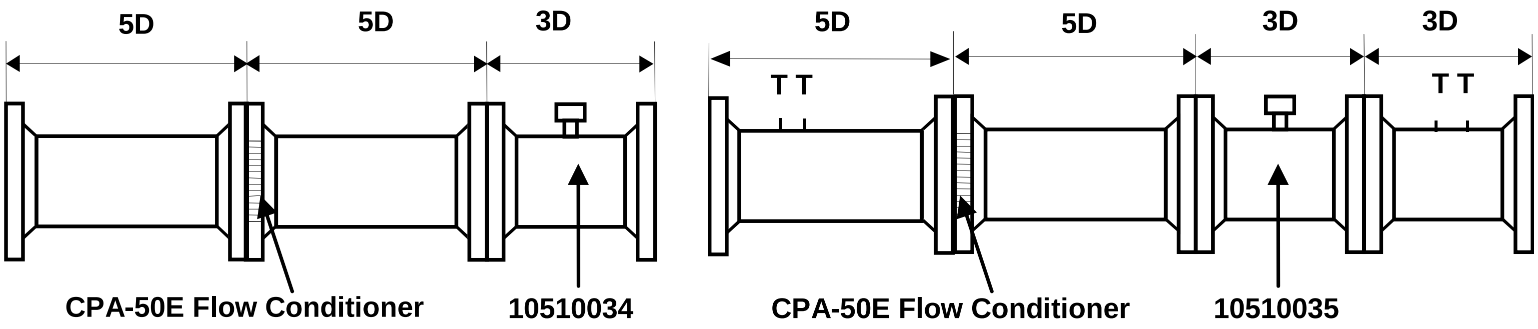
Terasen
(Penticton, BC)

Southwest Research
Institute
(San Antonio, Tx)

TransCanada
Calibration
(Ile des Chenes,
Manitoba)

Comparison of test facilities

The TeST artifact was comprised of two 8-inch diameter Instromet SM-RI-X-L G1000 turbine flow meters plumbed in series



TeST Watchdog Artifact Layout

Comparison of test facilities

TeST Artifact

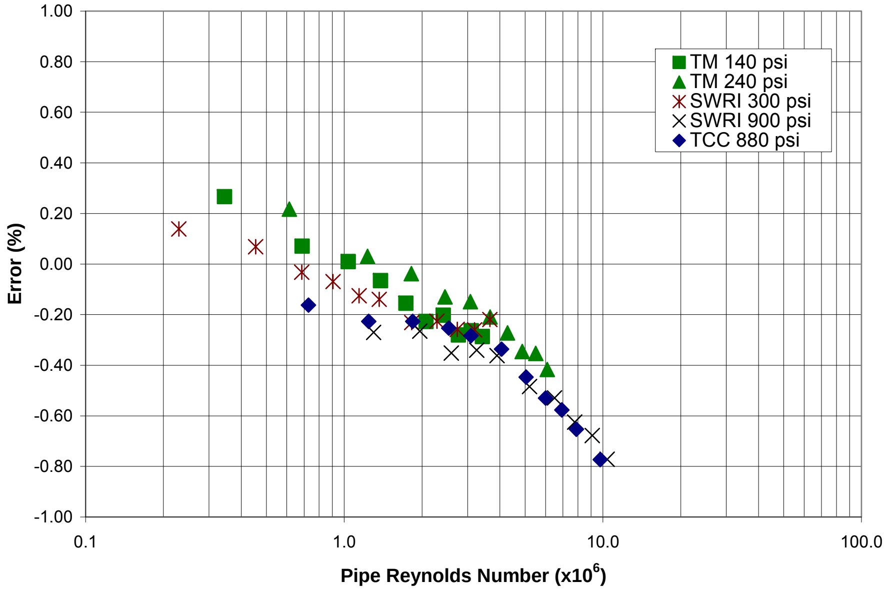
Dual Instromet turbine meter package with a CPA-50E plate upstream of each meter.
Each lab uses its own P&T measurement

Artifact - Sensus AAT-230 turbine meter

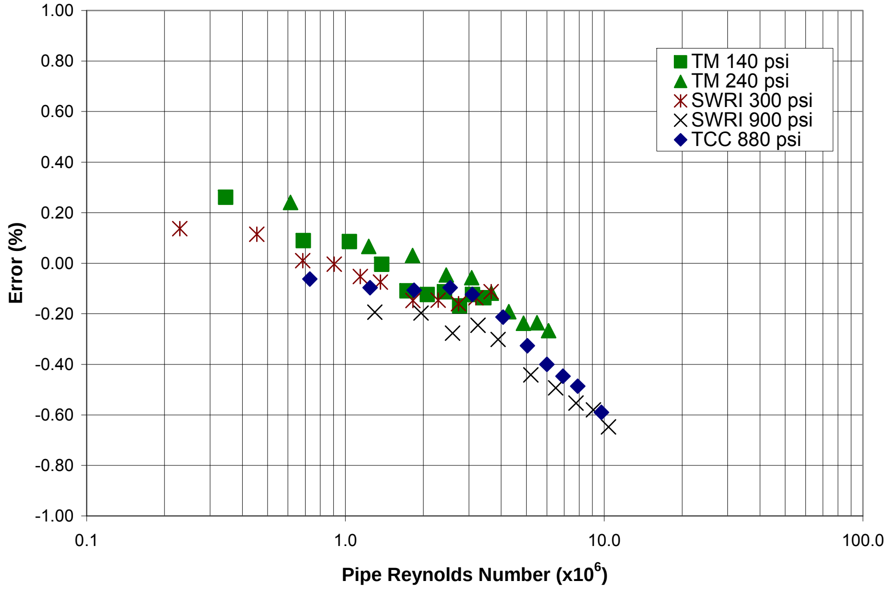
Comparison of test facilities

"WATCHDOG" artifact being tested at
the Triple Point facility - 2014

Comparison of artifact test data



Comparison of Test Results for Meter No. 10510034



Comparison of Test Results for Meter No. 10510035

Comparison of Test Facilities

Results show an agreement between the labs within ±0.08% of reading over the range of conditions tested.

This result is very similar to historical values of past inter-lab comparisons.

Comparison of test facilities

The artifact is shipped between the participating test facilities for inter-comparison tests.

In Summary

- ☐ What is Reynolds Number
- ☐ Reynolds Number and the Turbine Meter
- ☐ Reynolds Number Meter Proving
- ☐ The FortisBC Triple Point Meter Proving Facility
- ☐ Questions

Quote:

[To] mechanical progress there is apparently no end: for as in the past so in the future, each step in any direction will remove limits and bring in past barriers which have till then blocked the way in other directions; and so what for the time may appear to be a visible or practical limit will turn out to be but a bend in the road.

Osborne Reynolds

THANK YOU !

www.fortisbc.com/NaturalGas/Business/Measurement