Piston prover design with additional measurement capabilities and reduced flow interaction

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Abstract— High-speed clearance sealed piston provers for measuring gas flow rates have been available for over twenty years and have gained wide acceptance as a fast, cost-effective, primary calibration instrument for gas flow. High-speed piston provers are available for measuring flow rates from 0.5 sccm to 500,000 sccm with measurement uncertainties of up to 0.15% [1, 2, 3, 4]. This paper describes new advances in high-speed piston prover design.

I. Introduction

Many technologies exist to measure gas flow rates. A few are:

- Differential pressure instruments - measure pressure drop as gas flows past an obstruction.
- Constant-volume (rate-of-rise) instruments - measure pressure and temperature rise as gas fills an evacuated volume
- Thermal based instruments - measure heat transfer as gas flows over a heated element
- Constant-pressure positive displacement instruments, such as piston provers measure the physical displacement of a mechanical element by the flow of gas.

Piston prover designs have evolved over many years. This paper discusses the latest piston prover evolution featuring a horizontal piston design, which can measure corrosive gases, and automatically apply compressibility factor correction for non-ideal gases. The horizontal design while more complex than previous vertical tube design allows for faster measurement speed with reduced dynamic pressure changes that can introduce measurement uncertainty. Additionally, this new unit is engineered from corrosive resistant materials allowing many non-inert gases to be measured.

II. Piston Prover Design Cronology

1. Mercury-sealed provers were in use for many years and featured a rigid machined piston of significant mass that utilized a mercury seal between a glass tube and the outside diameter of the piston. A significant advantage to these instruments is the mercury provides a gas-tight low friction seal between the glass and the tube. However, mercury has the disadvantage of toxicity and the piston speed must be kept very slow to avoid loss of the mercury seal. Most mercury sealed piston provers have by now been removed from service due to environmental concerns. Mercury piston provers required a skilled operator to adjust a valve increasing the gas pressure on the bottom of the piston to the point that the piston floats. After this adjustment the valve is fully closed and the time required to slowly displace the piston is used to determine the volumetric gas flow rate.

Figure 1: Mercury Seal Piston Prover

2. High-speed vertical clearance-sealed piston provers have been in existance for more then 20 years and feature a piston machined to very tight tolerances minimizing clearance between the piston and tube, typically less then 10 microns. The tightly fitted piston reduces leakage around the piston to almost negligible rates. A 44mm diameter piston with a measurement range of 500 to 50,000 ccm will typically have a clearance leak rate of 1 ccm. Piston leakage for these instruments is measured and stored in the electronics memory and added to the flow measurement.

   The piston and cylinder are made of materials with matching coefficients of expansion, thus maintaining a consistant clearance dimension with changing temperature. Measurements are automated with a button push closing a bypass valve. The piston is displaced by the flowing gas through a set acceleration distance until a timing start point is reached and the time required to displace the piston through a calibrated volume is measured. After the measurement is complete, the bypass valve opens and the piston falls to the bottom of the tube at which time another measurement cycle can begin.

Figure 2: High-Speed Vertical Clearance-Sealed Piston Prover

3. High-speed horizontal clearance-sealed piston provers replace the vertical tube with a horizontal tube and a piston re-engineered for low-mass and low-friction. In comparison to the vertical tube, which requires a piston of sufficient mass to return the piston to the bottom of the tube, the horizontal tube uses a low mass low friction piston and valves which alternate the gas flow direction in the tube. As gas flows, optical sensors measure the piston oscillation across the tube. The horizontal tube-piston requires less gas pressure to displace the piston resulting in faster bi-directional readings and reducing pressure effects on the measured flow source.

Figure 3:High-Speed Horizontal Clearance-Sealed Piston Prover

III. CLEARANCE SEAL PISTON DYNAMICS

The flow dynamics for the piston in a clearance sealed piston prover can be modeled as a combined laminar Couette – Poiseuille Flow.

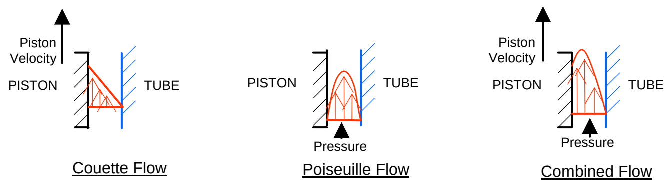

Figure 4: Piston Clearance Flow Dynamics

The Couette flow component represents the piston motion relative to the cylinder wall and is accounted for by setting the effective piston diameter at the mid-point between the tube inside diameter and the piston outside diameter. The Poiseuille flow component is driven by the pressure differential P displacing the piston and is accounted for by the piston leakage calibration. The piston leakage rate for a vertical piston prover is given by:

$$Q = (P/x)\, h^3 W/12\mu \quad (1)$$

Gas Leak rate: Q
Gas Pressure: P
Piston Height: x
Gap clearance: h
Piston radius: W
Gas Viscosity: μ

The gas pressure P once the piston of mass m is fully accelerated and assuming the piston moves without drag or is given by:

$$P = mg \quad (2)$$

For the horizontal piston prover the gas pressure P required to displace the piston is reduced by the coefficient of friction k of the piston material:

$$P = kmg \quad (3)$$

The horizontal piston prover piston was designed from materials with a coefficient of friction of 0.1 to 0.2. Additionally the horizontal piston was engineered with a lower mass piston further reducing the pressure. As previously noted, the piston leakage with a precision fitted piston is very small. But with the lighter mass piston of the horizontal design and the use of low friction materials, the pressure reduction to displace the piston proportionally reduces the piston leak rate Q.

IV. HORIZONTAL PISTON PROVER APLICATION ADVANTAGES

A piston prover initiating flow reading requires the measuring piston to accelerate. This acceleration will cause a pressure pulse to occur [2, 5]. For this reason, high-speed vertical pistons provers delay flow measurement to allow the piston to accelerate and the pressure pulse to subside [2]. Under typical laboratory conditions, the pressure pulse has no effect on measurement uncertainty. However, accurate flow measurements can be compromised on a system with large connecting gas volume between the source of the gas and the piston prover. The large connecting volume of gas between a flow generator and the piston prover act as storage for the gas as pressure changes occur. Many operators may be unaware of this or can not reduce connecting volumes. For this reason, it is desirable to minimize any pressure pulses produced during flow measurement by a piston prover.

The vertical design piston prover required a piston of sufficient mass to allow gravity to return the piston to the bottom of the tube after a measurement is complete. In the horizontal piston prover the piston is displaced in both directions by the flow of the gas. Since the horizontal piston does not use gravity to reset the piston the piston mass was reduced. In our instruments, the piston mass of the horizontal piston is approximately 50% less than the vertical piston. As previously noted for a horizontal piston, the pressure required to slide the piston is proportional to the weight of the piston times the coefficient of friction. Figure 3 shows the pressure pulse of a vertical piston prover and the reduced pressure pulse generated by the horizontal piston prover at the same flow rate.

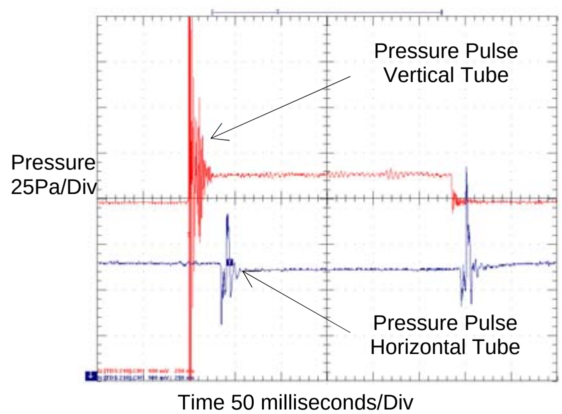

Figure 5: Piston Prover Pressure Pulse

V. CORROSIVE GAS MEASUREMNT

An additional advancement made in the engineering of the horizontal piston design was to add measurement capability for many corrosive gases. Internal components were designed from corrosive resistant materials: stainless steel, borosilicate glass, Teflon, and high purity graphite. In addition, positive displacement gas flow instruments measure volumetric flow. Since gases are compressible, volumetric flow measurements are converted to standardized flow measurements. The definition of a standardized flow rate is the volume of gas transported per unit time across a boundary with the measured gas volume converted to the volume the gas would occupy at a defined pressure and temperature. To make this conversion, a temperature transducer and pressure transducer inside the piston prover measure gas temperature and gas pressure. The conversion between volumetric flow and standardized flow can be derived from the ideal gas law giving the formula:

$$V_s = V_f \times (Pg/101.325) \times (273.15 + Ts)/(273.15+Tg) \quad (4)$$

Where V_s is the flow rate for standardized conditions, V_f is the measured volumetric flow rate, Pg is the measured gas pressure in kPa, Ts is the specified standardization temperature in degrees centigrade and Tg is the measured gas temperature in degrees centigrade.

While the ideal gas law provides sufficient accuracy when measuring inert gases across the narrow temperature and pressure of a typical laboratory environment, corrosive gases deviate from the ideal gas law. For this reason we have added compressibility factor correction needed for the non-ideal behavior of corrosive gases. Compressibility factor is a correction for gas property deviation from ideal behavior. With compressibility factor the conversion formula becomes:

$$Vs = V_f \times Z_{(Ps,Ts)}/Z_{(Pm,Tm)} \times (Pg/101.325) \times (273.15 + Ts)/(273.15+Tg) \quad (5)$$

The additional terms: $Z_{(PsTs)}$ is the gas compressibility factor at standardized conditions and $Z_{(Pm,Tm)}$ is the gas compressibility factor at the measured gas temperature and pressure. To automatically apply compressibility factor, the operator of the instrument selects the gas species being tested and a look up table in the instrument applies compressibility factor corrections. The compressibility factors used are derived from the NIST Reference Fluid Thermodynamics and Transport Properties Database (REFPROP) [6] .

VI. CONCLUSIONS

The horizontal design piston prover expands the use of high-speed clearance-sealed piston prover technology by reducing dynamic measurement pressure pulses. While under controlled conditions, pressure pulses do not present measurement difficulties. Many industrial installations requiring accurate flow measurement have large connecting or even unknown connecting volumes between the flow generator and the point of flow measurement. Similarly, many industrial applications, particularly the semiconductor industry, use corrosive gases in the manufacturing process. By engineering a piston prover with corrosive resistant material, non-inert gases can now be measured where previously measurement could only be done with great difficulty or with less accurate measurement technologies.

REFERENCES

[1] H. Padden, "High-speed prover system for cost-effective mass flow meter and controller calibrations", 2002 NCSL International Workshop and Symposium

[2] H. Padden, "Development of a 0.2% high-speed dry piston prover", 2003 Measurement Science Conference

[3] H. Padden, "Extending the range of gas piston provers", 7th Annual Symposium for Fluid Flow Measurement

[4] H. Padden, "Development of a Ultra low flow fast primary gas prover", 2003 Measurement Science Conference

[5] J. Kutin, G. Bobovnik, and I. Bajsic, "Dynamic effects in a clearance-sealed piston prover for gas flow measuremnts", Metrologia 48 (2011)

[6] Lemmon, E.W., Huber, M.L., McLinden, M.O. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2010