Experimental study of leakage flow effects in a clearance-sealed piston prover

G Bobovnik and J Kutin
University of Ljubljana, Faculty of Mechanical Engineering, Laboratory of Measurements in Process Engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia

E-mail: gregor.bobovnik@fs.uni-lj.si

Abstract. A piston prover measures the gas flow rate by determining the time interval that a piston needs to pass a known volume of gas at a defined pressure and temperature. In the clearance-sealed piston prover the leakage flow rate through the clearance between the cylinder and the piston represents the key contribution to the measurement uncertainty at the lowest measured gas flow rates. The article presents the measurement procedure for the leakage flow rate under operating conditions of the piston prover and evaluates some influence parameters on its magnitude; i.e., the measured flow rate, the gas viscosity and the flow cell inclination.

1. Introduction

Piston provers are commonly used volumetric primary standards for gas flow metering. The general principle of operation is based on determining the time interval that a piston needs to pass a known volume of gas at a defined pressure and temperature [1].

Figure 1a shows a schematic of the flow cell of a clearance-sealed realization of the piston prover [2-5], which is experimentally studied in this paper. The piston is made of graphite composite and the cylinder is made of borosilicate glass. The piston and the cylinder are closely fitted with a clearance of the order of 10 μm. The passage of the piston is detected by the infrared light emitters and sensors. The flow cell also contains the temperature and gauge pressure sensors positioned at the entrance to the cylinder. The base holds the computer, the timebase clock and the barometric pressure sensor. The mass flow rate is determined by the following measurement model:

\[
q_m = \rho(p_a,T)q_v(p_a,T), \quad q_v(p_a,T) = \left( \frac{V_m}{\Delta t} + q_{v,l} \right) \varepsilon_p,
\]

where \( \rho(p_a,T) \) is the gas density at the barometric pressure \( p_a \) and the inlet temperature \( T \), \( q_v(p_a,T) \) is the gas volume flow rate at these conditions, \( V_m \) is the measuring volume of the gas collected by the piston prover during the timing cycle \( \Delta t \), where \( V_m \) already considers the effect of the Couette component of the clearance leakage flow, \( q_{v,l} \) is the Poiseuille component of the clearance leakage flow and \( \varepsilon_p \) is the gas-density correction factor [2].

The aim of this paper is to study the effects on the Poiseuille leakage flow component, which is driven by a pressure difference on the piston. Considering that the relative pressure difference \( \Delta p/p_a \) and the relative piston-cylinder clearance \( \delta/D \) are relatively small, and the piston is quiescent in the central position within the cylinder, the Poiseuille leakage volume flow rate can be written as:
where $D$ is the piston diameter, $H$ is the piston height and $\mu$ is the gas dynamic viscosity. The leakage flow rate can be significantly influenced by the position and the dynamics of the piston. For example, considering the quiescent piston in its extreme eccentric position, the Poiseuille leakage volume flow rate is for 2.5 times higher than one resulting from (2). For that reason, managing the calibration and measurement capabilities of the clearance-sealed piston prover requires that the leakage flow rate is experimentally determined. In this paper, we focus on the identification and the evaluation of different potential influence parameters on the magnitude of the Poiseuille leakage flow.

![Diagram](image-url)

**Figure 1.** Piston prover (a) schematical representation, (b) measuring system for the leakage flow rate.

### 2. Dynamic summation method

The dynamic summation method [6] is used to measure the leakage flow rate $q_{vl}$ in the clearance-sealed piston prover (Sierra Instruments, Cal-Track SL-800, SL-800-10 flow cell, flow range for air: 1.2 g/min – 600 mg/min) using the measuring system shown in figure 1b. The gas is supplied from two stable flow sources (2 MFCs, Bronkhorst F-201CV, full scale for air: 13 mg/min) to two parallel flow branches, each restricted by a valve (3-way pneumatic valves), which reunite before the inlet to the piston prover. During the measurement the uncorrected readings of the piston prover are recorded, which is achieved by setting $q_{vl}$ in (1) to zero. So the actual mass flow rate ($q_m$) is the sum of the uncorrected reading of the piston prover ($q_m^*$) and the leakage mass flow rate through the piston cylinder clearance ($q_{ml}$). The mass flow rate is consecutively measured from each flow source separately ($q_{m1}$, $q_{m2}$) by closing the valve in the other branch, as well as from both flow sources simultaneously ($q_{m1+m2}$). By closing a valve in a particular branch the gas is diverted to the gas extraction system. Assuming that all mass flow rate sources remain stable during the measurement, the following holds true:

$$q_{m1} + q_{m2} = q_{m1} + q_{m2} + q_{n1} + q_{n2}$$

Finally, the leakage volume flow rate as defined in the measurement model of the piston prover (1) is calculated as $q_{vl} = q_{n1} / \rho e_{p}$, where $\rho$ and $e_{p}$ are taken as the average values during the measurement.
Using the following sequence of measured flow rates: \( q_{m1}, q_{m1+m2}, q_{m2}, q_{m1+m2} \ldots \), multiple values of leakage flow rate (\( q_{v,l,i} \)) are obtained. The average leakage flow rate and its expanded uncertainty for \( N \) measurement results are estimated by:

\[
\overline{q}_{v,l} = \frac{1}{N} \sum_{i=1}^{N} q_{v,l,i}, \quad U\left(\overline{q}_{v,l}\right) = \frac{t_{N-1}}{\sqrt{N}} \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left( q_{v,l,i} - \overline{q}_{v,l} \right)^2},
\]

where \( t_{N-1} \) is the Student factor for \( N-1 \) degrees of freedom and 95.45% confidence interval.

Three different gases were used in the tests: dry air, nitrogen (99.999% purity) and oxygen (99.95% purity). The physical and transport properties of gases were calculated using REFPROP database [7].

To ensure stable temperature conditions during the tests, the entire measuring system is placed into the temperature chamber (Kambič KK-340CHLT). The temperature in the chamber is measured by the Pt100 based measuring system (TetaTec 624T 379 + PicoTech PT-104). The inclination of the flow cell from vertical is measured by the digital spirit level (Laserliner, DigiLevel Plus 25). The communication and control of all elements, as well as the processing of the measurement signals, is realized using LabVIEW software (National Instruments, Ver. 10.0).

3. Test results
The tests were performed at constant temperature in the chamber equal to 22.1 °C ± 0.1 °C. If not stated otherwise, the gas is air, the flow cell angle of inclination (from vertical) is equal to 0° and the supplied mass flow rate from both MFCs is set to 50% of their full scale value (\( q_{m1} \approx q_{m2} \)). For a single test, the average leakage flow rate (\( q_{v,l} \)) and its expanded uncertainty are based on twenty consecutive measured values. A representative example of the measured leakage flow rates, including their average value and the estimated expanded uncertainty is shown in figure 2.

Figure 3 shows measured leakage flow rates and their expanded uncertainties (presented with error bars) for four different supply mass flow rates. Several tests were made at each supply mass flow rate. It can be seen that there is no obvious trend of the leakage flow with respect to the supply mass flow rate. On the other hand, the estimated uncertainties increase with the higher supply mass flow rate, which is probably related mainly to the stability of the MFCs used in the tests. Considering the value of the pressure difference below and above the piston and the results of the dimensional calibrations of the piston and the cylinder, the measured leakage flow rate is for about 1.15 times higher than the one resulting from (2).

3.1 Gas viscosity effect
The gas viscosity effect was estimated by carrying out additional tests with nitrogen and oxygen. The tests were repeated three times for each gas. The results presented in figure 4 confirm the predictions of the theoretical model (2), which states that the leakage flow rate is inversely
The leakage flow rate is inversely proportional to the dynamic gas viscosity. The average leakage flow rate of nitrogen, which viscosity is for 3.5 % lower compared to air, increases for about 3.2 %. Similarly, the leakage flow rate of oxygen, which viscosity is for 11.6 % higher compared to air, decreases for about 11.2 %. The results exhibit similar reproducibility of measured leakage flow rates for all gases.

The last set of tests was conducted to evaluate the influence of the flow cell inclination (from vertical). The tests were made for four different angles of inclination and their estimated measurement uncertainty is about 0.2°. Multiple repetitions that were carried out show characteristic levels of the leakage flow rate at each angle of inclination (figure 5). It is important to emphasize that the angle of inclination was always changed between two successive tests. It can be seen that in the initial stage when the angle is increased up to 2.5°, the leakage flow rate decreases (for about 2.5 %/°), but increases again at the angle of inclination of 5°. The influence of inclination is probably related to the change in the average piston position within the cylinder.

4. Conclusions
The paper deals with the leakage flow related effects in the clearance-sealed piston prover. Using the described summation method the leakage flow rate was measured during its normal operation. The tests show that the leakage flow rate equals approximately 23 % of the flow rate at the lower end value of the measuring range (1.2 g/min). Its uncertainty represents the key contribution to the uncertainty of the measured mass flow rate in the lower flow range. The tests showed that the most important leakage flow rate effects are the gas viscosity and the inclination of the flow cell of the piston prover. For both effects the results are reproducible, which indicates the possibility for the correction of both effects. The leakage flow rate is inversely proportional to the gas viscosity, which is in accordance with the theoretical prediction made for the Poiseuille flow. The additional tests for the estimation of the leakage flow rate at different temperatures within the operational range of the piston prover are planned in the future. The temperature could affect the gas viscosity and also other influential parameters, such as the clearance thickness between the piston and the cylinder.

5. References
[1] Berg R F, Gooding T and Vest R E 2014 Flow Meas. Instrum. 35 84–91
[2] Kutin J, Bobovnik G and Bajišić I 2011 Metrologia 48 123–32
[3] Kutin J, Bobovnik G and Bajišić I 2013 Metrologia 50 66–72
[4] Kutin J, Bobovnik G and Bajišić I 2015 Metrologia 52 857–63
[5] Bobovnik G, Kutin J and Bajišić I 2016 Metrologia 53 1061–68
[6] Padden H 2006 Comparisons of viscous-sealed provers with LNE and studies of piston-cylinder leakage 6th Int. Symp. on Fluid Flow Measurement (Queretaro: Mexico)
[7] Lemmon E W, Huber M L and McLinden M O 2010 NIST Reference Fluid Thermodynamic and Transport Properties—REFPROP Version 9.0 (Gaithersburg, NIST)