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International comparison of a NIST primary standard with an NRLM transfer standard for small mass flow rates of nitrogen gas

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Abstract. International comparisons of small gas flow measurements were carried out between the National Institute of Standards and Technology (NIST) in the United States of America and the National Research Laboratory of Metrology (NRLM) in Japan. An NRLM transfer standard package composed of sonic venturis, two pressure transducers, and two temperature sensors was calibrated using the NRLM primary standard for low gas flows (a gravimetric system) and was brought to the US in April 1996. The NRLM transfer standard was compared with the NIST Fluid Flow Group piston provers (a volumetric system) using mass flow rates of nitrogen between 0.4 g/min and 11.5 g/min. The mean differences between the NRLM transfer standard and the NIST Fluid Flow Group piston provers ranged from –0.09 % to + 0.13 %.

1. Introduction

International comparisons between national laboratories are an important activity for finding and eliminating systematic errors that occur in calibration facilities and for verifying uncertainty analyses [1]. Interlaboratory comparisons determine the agreement between the primary flow standards of national laboratories and thereby allow efficient international trade. Comparisons in the field of gas flow measurements are particularly difficult because there are no "identity standards" of flow as there are for length or mass, for example, and as a result flow standards are complex systems often involving numerous measurements (and calibrations) of length, mass, time, temperature, and pressure. In addition, the quality of the velocity profile provided for the meter under test (the approach condition) is an issue in flow calibration. Once such a complex system is put in order by thorough internal checks, comparison with another independently calibrated primary flow standard is useful to test what problems or systematic errors may remain. In this way, the international metrology community continuously refines its flow measurements.

Low mass flow rate measurements of gas are needed for semiconductor manufacturing, medical and chemical analyses, and for environmental measurements. The manufacturers and owners of flow meters used for small gas flows such as thermal mass flow meters, laminar flow elements, critical venturis, and turbines are continually working to improve their design and accuracy [2]. Accurate primary flow standards are a necessary element for furthering the efforts to improve low gas flow rate measurements.

The Fluid Flow Group at the NIST has a primary standard for low gas flows; a set of three mercury-sealed piston provers which cover a flow range from 0.05 g/min to 33 g/min. The medium and large piston provers used in this interlaboratory comparison measure flow with a relative standard uncertainty of 9×10^{-4} (level of confidence of approximately 67 %) [3]. Relative standard uncertainties that provide an approximate level of confidence of 67 % are used in this paper in accordance with current guidelines covering international comparisons. The NIST developed a transfer standard based on a set of three redundant sonic nozzle flow measurements in 1992 that has a flow relative uncertainty of 1.2×10^{-3}. This transfer standard has been used to perform comparisons between the Fluid Flow Group piston provers and other primary flow standards within the United States [4]. The Fluid Flow Group piston provers have also been compared with other primary flow standards within the NIST.

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In 1994, the Fluid Measurement Section of the NRLM designed and built a gravimetric calibration facility and established a primary standard for small mass flow rates of gas with a maximum relative uncertainty of 1.1×10^{-3} [5]. Furthermore, the NRLM has constructed a transfer standard with interchangeable sonic venturis, pressure transducers, and temperature sensors, which has been calibrated using the NRLM primary standard, and has a flow relative uncertainty of 1.1×10^{-3} over the range of flows used in this comparison.

This report presents the results of an interlaboratory comparison performed in April 1996 over mass flow rates from 0.4 g/min to 11.5 g/min (0.3 L/min to 10 L/min) using the NRLM transfer standard and the NIST Fluid Flow Group piston provers. (All volumetric flows are referenced to 20 °C and 101 325 Pa conditions). The data show that the NRLM transfer standard and the NIST piston provers are in agreement within 0.13 %. This agreement is considered good when the uncertainties of the two facilities are taken into account, and indicates that the uncertainty estimates are reasonable.

2. NRLM primary standard for small gas flows

The NRLM gravimetric primary standard for small gas flows diverts flow into an evacuated cylinder, measures the mass of the cylinder before and after the collection, and divides the mass by the collection time interval to attain the mass flow rate. A description of the facility along with an uncertainty analysis has been presented previously [5]. Over the entire flow range of the facility, the worst-case relative uncertainty of the NRLM primary standard is 1.1×10^{-3}. The relative uncertainty is less than 1.1×10^{-3} over certain flow ranges.

3. NRLM transfer standard for small gas flows

The NRLM transfer standard was designed to be easily transported to other laboratories for comparison. The other design priorities were that it be rugged, have sensor redundancies, and maintain its calibration despite transportation (see Figure 1).

Figure 2 is a schematic representation of the NRLM transfer standard. The system includes a pressure regulator and filter, followed by a block to reduce pressure fluctuations and allow the gas to reach thermal equilibrium with the room. A needle valve is used to control the pressure upstream of the venturi and hence the flow rate. A pair of platinum resistance temperature devices (RTDs) is available to acquire the gas temperature upstream of the venturi. Two pressure transducers measure the pressure upstream and downstream of the venturi, allowing the user to measure the pressure ratio across the nozzle and assure critical flow through the venturi. The pressure transducers are removed for hand carrying during shipment of the transfer standard. A laptop computer uses a GPIB interface to read the pressure and temperature gauges, calculate the flow, and write data to file. The pressure transducer and temperature sensor used in the venturi flow calculation can be changed by the user. A flowmeter or calibration facility can

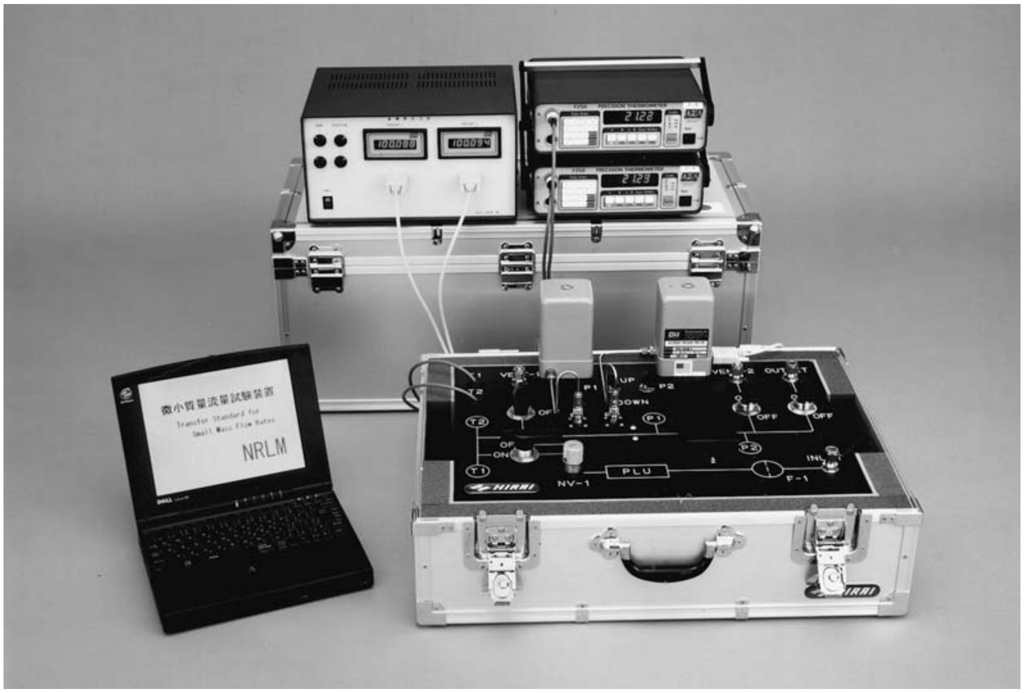


Figure 1. The NRLM transfer standard.

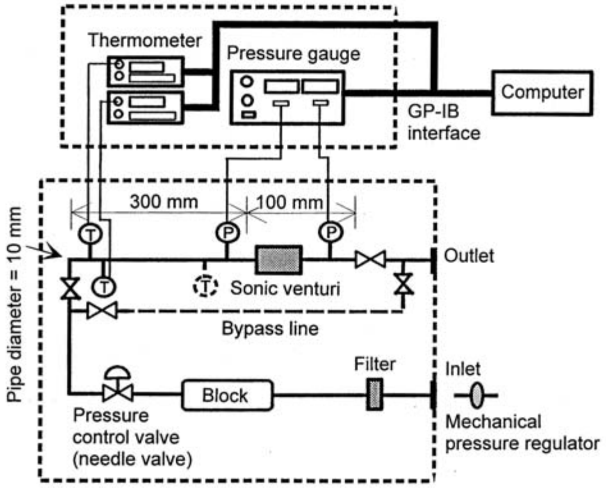


Figure 2. Schematic of the NRLM transfer standard.

be connected upstream or downstream of the transfer standard depending on the measurement conditions.

Three sonic venturis have been machined into stainless-steel discs that can be interchanged in a holder depending on the flow rate of interest. Figure 3 shows the venturis with details of their throat diameters and nominal flow rates. The discharge coefficients of the sonic venturis have been fitted as a function of the theoretical Reynolds number based on calibrations with the NRLM primary standard. The theoretical Reynolds number, Re_{th}, is based on the theoretical mass flow rate, $\dot{m}_{\mathrm{th}}$, calculated from the throat diameter, D, the viscosity at the stagnation conditions, μ_0, and the throat temperature and pressure conditions. The throat pressure and temperature are calculated using stagnation pressure and temperature measurements and by assuming isentropic flow in the converging section of the venturi.

The theoretical mass flow rate is

$$\dot{m}_{\mathrm{th}} = (P_0 \cdot A \cdot C^*)/(R \cdot T_0 \cdot Z)^{1/2}, \qquad (1)$$

where A is the cross-sectional area of the venturi throat, R is the gas constant, P is pressure, and T is temperature, with the subscript 0 referring to stagnation conditions. The variable Z is the compressibility factor and it is assumed to be unity, while C^* is the critical flow factor, calculated from the specific heat ratio, γ, as follows:

$$C^* = \gamma^{1/2} \cdot [(\gamma+1)/2]^{(\gamma+1)/(2-2\cdot\gamma)}. \qquad (2)$$

Using the theoretical mass flow, the theoretical Reynolds number can be calculated by

$$Re_{\mathrm{th}} = (4 \cdot \dot{m}_{\mathrm{th}})/(\pi \cdot D \cdot \mu_0). \qquad (3)$$

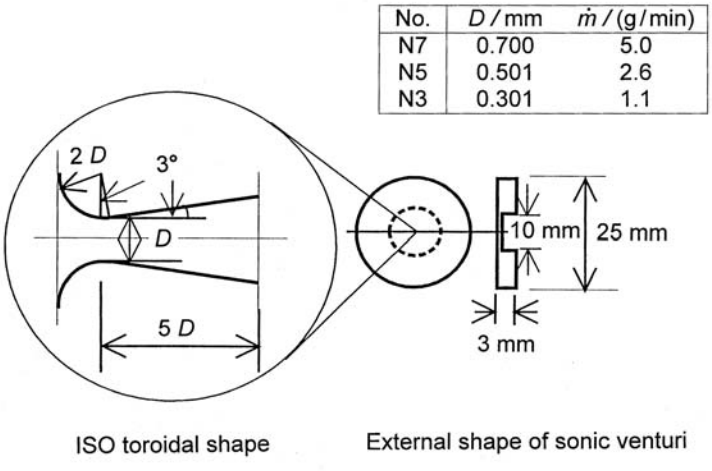
The mass flow rate measured by the sonic venturi, $\dot{m}$, is calculated from the following equation:

$$\dot{m} = C_{\mathrm{d}} \cdot \dot{m}_{\mathrm{th}}. \qquad (4)$$

The discharge coefficients, C_{d}, for the three sonic venturis were determined from best-fit equations with the theoretical Reynolds number as follows:

$$\begin{aligned} C_{\mathrm{d}} &= 1.014\,17 - 3.721\,36 \cdot (Re_{\mathrm{th}})^{-1/2} \quad \text{for N7}, \\ C_{\mathrm{d}} &= 1.006\,94 - 3.195\,50 \cdot (Re_{\mathrm{th}})^{-1/2} \quad \text{for N5}, \\ C_{\mathrm{d}} &= 1.005\,96 - 3.783\,00 \cdot (Re_{\mathrm{th}})^{-1/2} \quad \text{for N3}. \end{aligned} \qquad (5)$$

A list of the uncertainty components for the NRLM transfer standard is given in Table 1. The uncertainty of the discharge coefficients of the sonic venturis depends on the uncertainty of the NRLM primary standard, the repeatability of the measurements, the standard deviation of the discharge coefficient curve fit residuals, and the uncertainty of the theoretical Reynolds number. The relative uncertainty of the calibration facility listed in Table 1 is calculated for the flow range utilized, and is not necessarily the maximum relative uncertainty for the



No.	D / mm	$\dot{m}$ / (g/min)
N7	0.700	5.0
N5	0.501	2.6
N3	0.301	1.1

Figure 3. Schematic of the NRLM sonic venturis. ISO refers to the International Standards Organization.

NRLM primary standard. The pressure sensors used in the transfer standard were calibrated between 0 kPa and 250 kPa using the standard piston gauge at the NRLM. The relative uncertainty of the pressure measurements (including components due to the NRLM piston gauge and calibration residuals) was less than 4×10^{-4}. The 100 Ω platinum RTDs were calibrated over the range 15 °C to 35 °C and the uncertainties of the temperature measurements were less than 0.1 °C. By analysing the propagation of uncertainties through (1) and (3), the relative uncertainty of the theoretical Reynolds number calculated from the measurements of these sensors was 4.3×10^{-4}. In the present comparison, three sonic venturis were operated at a pressure ratio of about 0.45 at three higher flow rates, 2.1 g/min, 3 g/min, and 11.5 g/min. These sonic venturis, however, were calibrated at the pressure ratio of 0.4. Additional experiments on the relation between the discharge coefficient and the pressure ratio showed that there is a change of 0.03 % in the discharge coefficient at these two pressure ratios. This was included in the uncertainty analysis in the category labelled "operating condition". The values of the thermophysical properties used to calculate the mass flow rates were obtained from polynomial best-fit functions fitted to tabulated reference data [6]. The polynomial functions fit the tabulated data with a relative standard uncertainty of 1×10^{-4}.

The combined relative standard uncertainty of the NRLM transfer standard mass flow rate is calculated by taking the root-sum-of-squares of the uncertainty components listed in Table 1. The combined relative uncertainties for the sonic venturis in the transfer standard are 1.1×10^{-3} for all three venturis.

The transfer standard has two sets of temperature and pressure sensors to allow checks on whether damage has occurred during shipping. In particular, after the flow rate is measured using one pair of sensors, a measurement of the flow rate using the other pair of sensors is repeated without changing the flow conditions. If the results of these two measurements do not agree, it indicates that some calibration drift has occurred, perhaps during transport of the transfer standard. If both flow measurements are the same, the flow rates are considered to be measured correctly.

Table 1. Summary of uncertainties, NRLM transfer standard.

Uncertainty category	100 × Relative standard uncertainty		
	N3	N5	N7
Uncertainty of calibration facility	0.068	0.074	0.071
Repeatability of calibration facility	0.030	0.030	0.030
Uncertainty of theoretical Reynolds number	0.043	0.043	0.043
Deviation from the fitted curve	0.041	0.051	0.044
Operating condition	0.015	0.015	0.015
Uncertainty of theoretical mass flow rate	0.043	0.043	0.043
Combined relative standard uncertainty	**0.11**	**0.11**	**0.11**

4. NIST Fluid Flow Group piston provers

The NIST Fluid Flow Group operates a set of three piston provers which covers a flow range from 0.05 g/min to 33 g/min (3.7×10^{-5} m^3/min to 3.0×10^{-2} m^3/min) [3]. The three provers are mounted together in a console and connected by a manifold to a single inflow line. In the piston prover system (Figure 4), the metered gas is diverted by valving into a glass cylinder to raise a mercury-sealed piston. As the piston rises through the cylinder, it successively starts and stops a timer by blocking the light passing through machined slits at the ends of the collection volume. The temperature and pressure of the gas entering the collection volume are measured with a temperature sensor and an absolute pressure gauge. The temperature and pressure are used to calculate the density of the collected gas, and the density is used to convert the measured volumetric flow rate into a mass flow rate.

The principles of mass conservation, as applied to the piston prover, can be written:

$$\dot{m} = (\rho_\mathrm{c} \cdot V_\mathrm{c})/\Delta t + (\Delta\rho_\mathrm{a} \cdot V_\mathrm{a})/\Delta t + \dot{m}_l. \qquad (6)$$

Here, V_c is the collection volume generated by the piston displacement during the collection time interval, Δt. The quantity V_a is the remaining volume in the system; the volume of the flowmeter being tested, the approach piping connecting the meter under test to the cylinder, the tare volume in the prover, and tubing for pressure transducer connections. The mean gas density in the collection volume, ρ_c, is calculated from pressure and temperature measurements made during the run, and $\Delta\rho_\mathrm{a}$

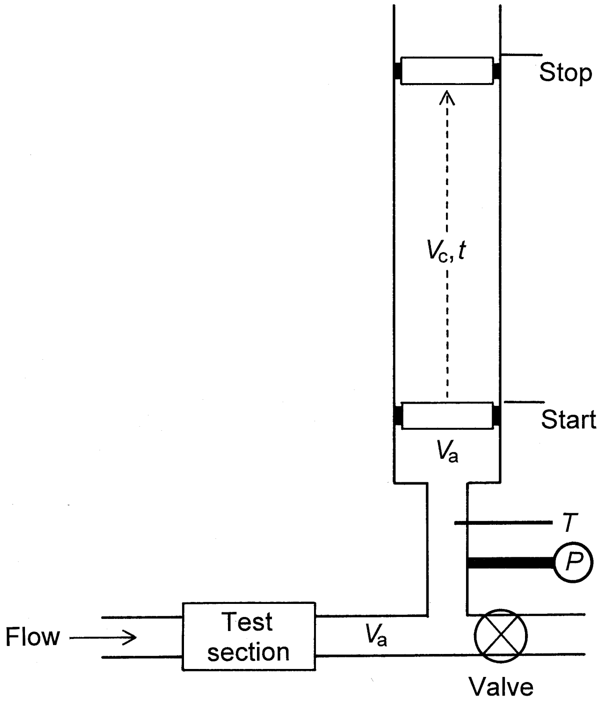


Figure 4. Schematic of the NIST primary standard. See nomenclature at end of paper for symbols.

Table 2. Summary of uncertainties, NIST Fluid Flow Group piston provers.

Uncertainty category	100 × Relative standard uncertainty			
	Medium prover		Large prover	
Collection volume density		**0.061**		**0.053**
Temperature	0.14 K	0.047	0.11 K	0.037
Pressure	0.022 kPa	0.022	0.022 kPa	0.022
Fitting function		0.029		0.029
Experimental data		0.012		0.012
Collection volume	**0.078 cm^3**	**0.011**	**2.448 cm^3**	**0.033**
Cylinder diameter	2.0×10^{-4} cm	0.009	2.3×10^{-3} cm	0.032
Collection length	5.0×10^{-4} cm	0.001	5.0×10^{-4} cm	0.001
Thermal expansion	4.6×10^{-2} cm^3	0.006	4.8×10^{-1} cm^3	0.006
Collection time	**0.0102 s**	**0.058**	**0.0102 s**	**0.061**
Timer calibration	1.0×10^{-4} s	0.001	1.0×10^{-4} s	0.001
Timer actuation	8.5×10^{-3} s	0.057	8.5×10^{-3} s	0.057
Piston rocking		0.012		0.023
Storage effects		**0.007**		**0.001**
Combined relative standard uncertainty		**0.09 %**		**0.09 %**

is the change in the mean density of the gas in the approach piping that occurs during the collection interval.

The second term of (6) accounts for "storage effects" in the approach volume, V_a: if the density of the gas in V_a is increasing (as a result of decreasing temperature or increasing pressure), then gas is effectively "stored" in the connecting piping and the flow as measured by the piston prover is less than the flow through the meter under test during the collection interval. Conversely, if the gas within the connecting piping is expanding, then the flow determined by the piston prover is greater than the flow passing through the meter under test. The term $\dot{m}_l$ is included to represent flows leaking from the system. This term is zero or negligible as leakage checks are performed before calibrations are begun.

The uncertainty of the mass flow measurements determined by the piston prover can be analysed by considering the uncertainties of the measured quantities in (6). The mass flow measurement is subject to uncertainties in the determination of the collection volume, V_c, the timing interval, Δt, and the density, ρ. The uncertainty of the gas density arises from uncertainties in the measurement of the temperature and pressure of the gas within the collection volume, as well as the goodness of fit of the best-fit function used to calculate the density, and the quality of the experimental data used to determine the function. The uncertainties in temperature and pressure measurements are related to calibration quality, sampling errors, and sensor drift over time. The uncertainty of the collection volume derives from uncertainties in measuring the diameter of the cylinder and in measuring the separation between the start and stop location (the collection length), as well as the effects of thermal expansion resulting from variations in room temperature. The uncertainty of

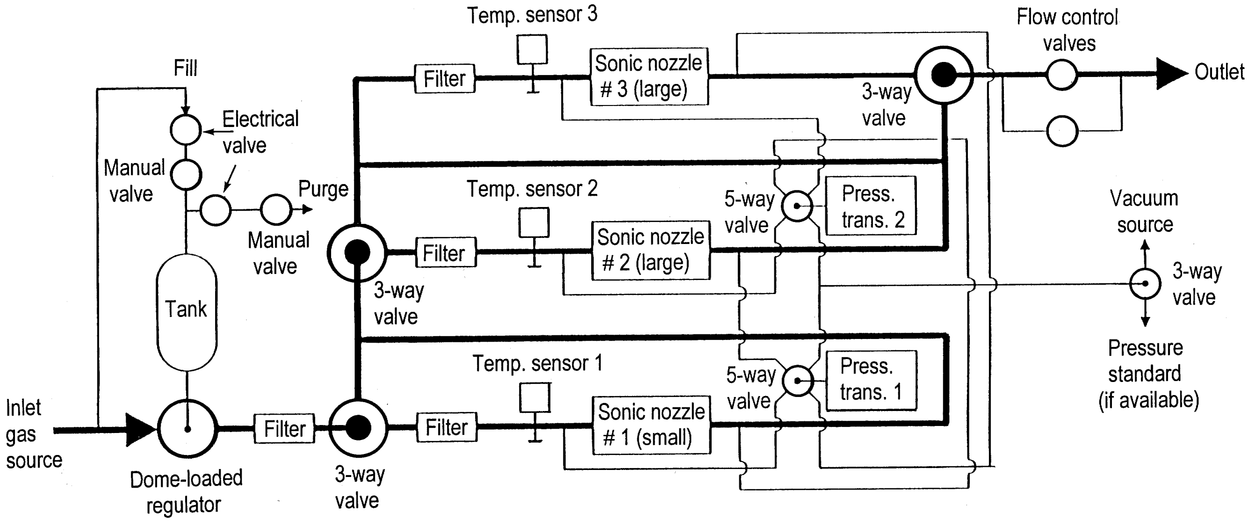


Figure 5. Schematic of the NIST primary standard.

the timing interval measurement can be traced to the uncertainty of the timer calibration, the uncertainties of its actuation by the start and stop switches, and any rocking of the piston as it passes the switches. The term representing storage effects in (6) becomes an uncertainty source if the change in density within the connecting piping is non-zero during the collection period due to changes in temperature and pressure in the connecting piping.

These uncertainties have been studied experimentally and quantified [3, 7]. The results of the uncertainty analysis for the medium and large piston provers (used in the NIST/NRLM comparison) are given in Table 2, where it can be seen that the combined relative standard uncertainty of the flow measurement is 9×10^{-4} for the two provers. The uncertainty values in Table 2 are combined Type A and Type B uncertainties, with the Type B component generally much larger than the Type A.

5. NIST Fluid Flow Group transfer standard for small gas flows

The NIST Fluid Flow Group transfer standard for small gas flows was used only to establish a constant flow during the present comparison so it is only briefly described [4]. The NIST transfer standard was designed to be portable and to measure the gas flow rate with redundancy to ensure performance stability. The design therefore uses tandem sonic nozzles, temperature sensors, and pressure sensors with pertinent redundant checks, to allow diagnosis of sensor drift or damage. Tandem nozzles also allow checks of the stability of the flow through the transfer standard by monitoring the ratio of the upstream and downstream nozzle Reynolds numbers and by checking the correlation of the flow measurements made by the two nozzles.

Figure 5 is a schematic of the NIST transfer standard. The standard comprises three sonic nozzles, as well as three thermistors and two pressure transducers to measure the temperature and pressure of the gas upstream from each nozzle. Three-way valves permit the flow path through the nozzles to be varied, and five-way valves permit connection of the pressure transducers to various locations in the piping system upstream and downstream of the nozzles as well as to an external pressure-calibration system. The sonic nozzles are calibrated and used at only two flow rates, 0.4 g/min and 1.0 g/min of nitrogen (0.34 L/min and 0.86 L/min, or nozzle 1 Reynolds numbers of 6700 and 16700).

6. Test description

In April 1996, comparisons between the NRLM transfer standard and the NIST piston provers were carried out at five flow rates of nitrogen, 0.4 g/min, 1.0 g/min, 2.1 g/min, 6.0 g/min, and 11.5 g/min (0.34 L/min, 0.86 L/min, 1.8 L/min, 5.2 L/min, and 9.9 L/min). For the two smallest flow rates, the NRLM transfer standard and the NIST piston prover were set up in a parallel arrangement as shown in Figure 6a, and the NIST

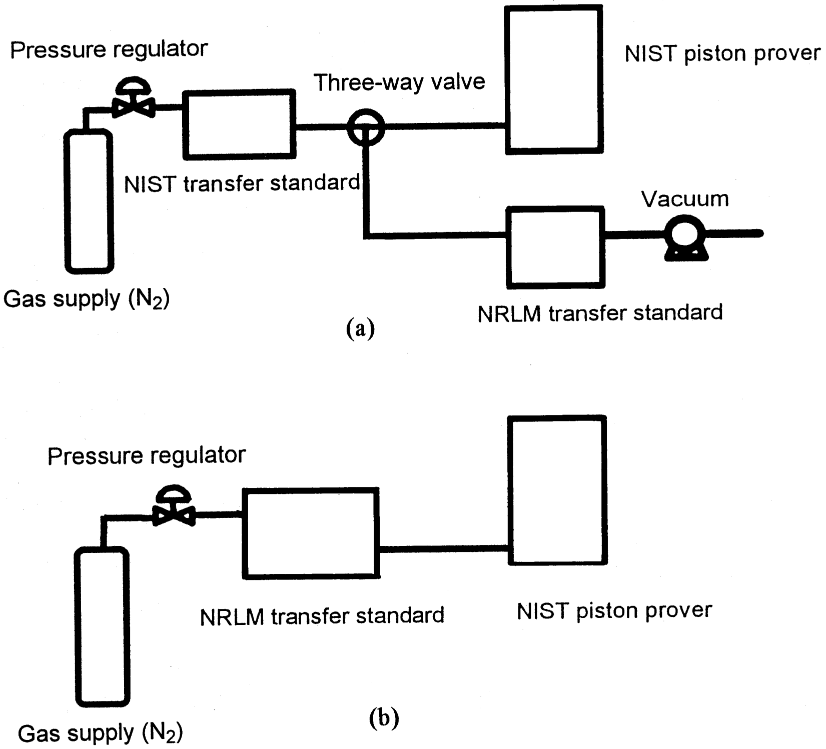


Figure 6. Experimental setups for the comparison tests: (a) parallel arrangement; (b) series arrangement.

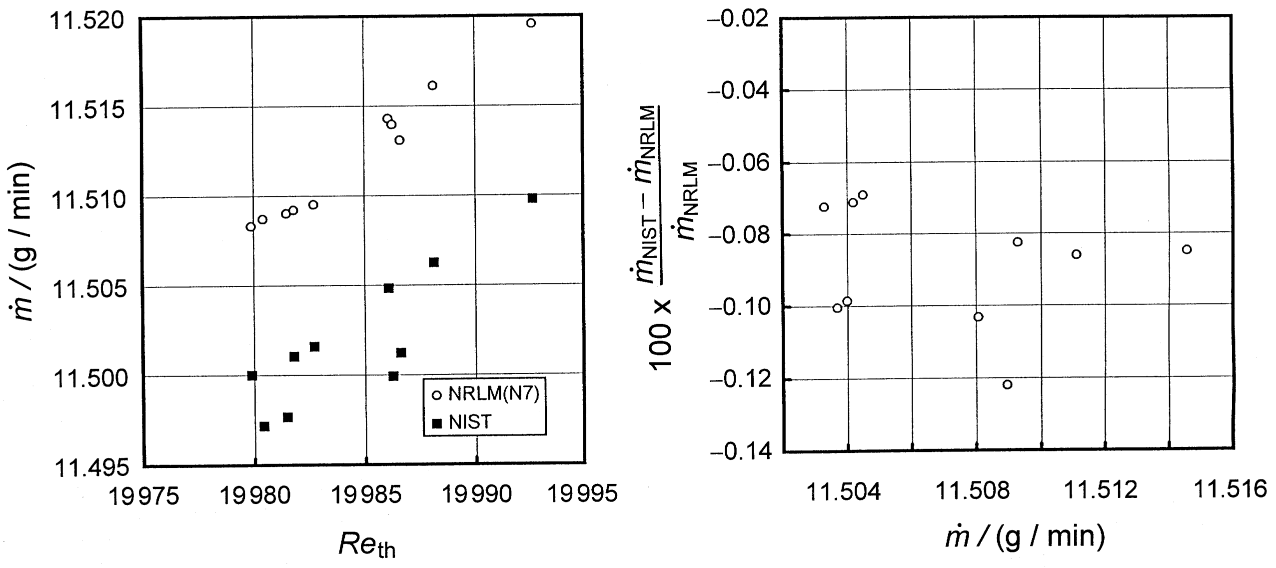


Figure 7. Data from the 11.5 g/min case: NRLM and NIST flows versus theoretical Reynolds number, and the percentage deviation between NRLM and NIST versus the NRLM mass flow rate.

transfer standard was used to establish a metered, constant flow. A three-way valve was used to switch the flow between the NIST piston prover and the NRLM transfer standard. After a flow determination was made by the NRLM transfer standard, the flow was switched to the NIST piston provers to collect flow data, then the flow was switched back to the NRLM transfer standard and the process was repeated. For some tests, only one flow measurement per switch was collected by the piston prover, while for others, a set of five measurements was collected and averaged for comparison with the NRLM flows. The Reynolds number indicated by the NIST transfer standard was recorded so that corrections could be made to the data if significant changes in the flow were observed over time. However, the largest change in Reynolds number observed between a change in the flow path was 0.01 % and hence corrections based on the NIST transfer standard Reynolds numbers were not made.

The flow test was set up in a parallel fashion because the NRLM venturi C_{d} curves had been characterized with near-vacuum pressure conditions on the downstream side. Using the NRLM venturis with atmospheric pressure on the downstream side (as needed by the mercury-sealed piston prover) would result in Reynolds numbers greater than the range over which they had been calibrated. For flows greater than 1 g/min, the available vacuum pump was not large enough to maintain a critical pressure ratio across the NRLM venturis, hence the series arrangement shown

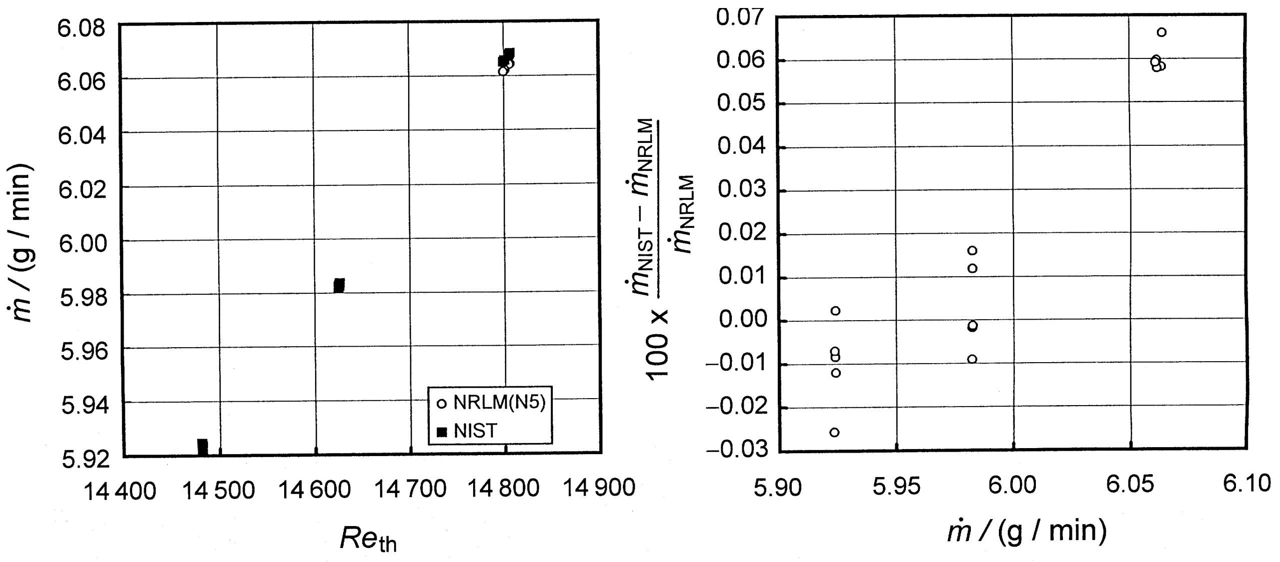


Figure 8. Data from the 6.0 g/min case.

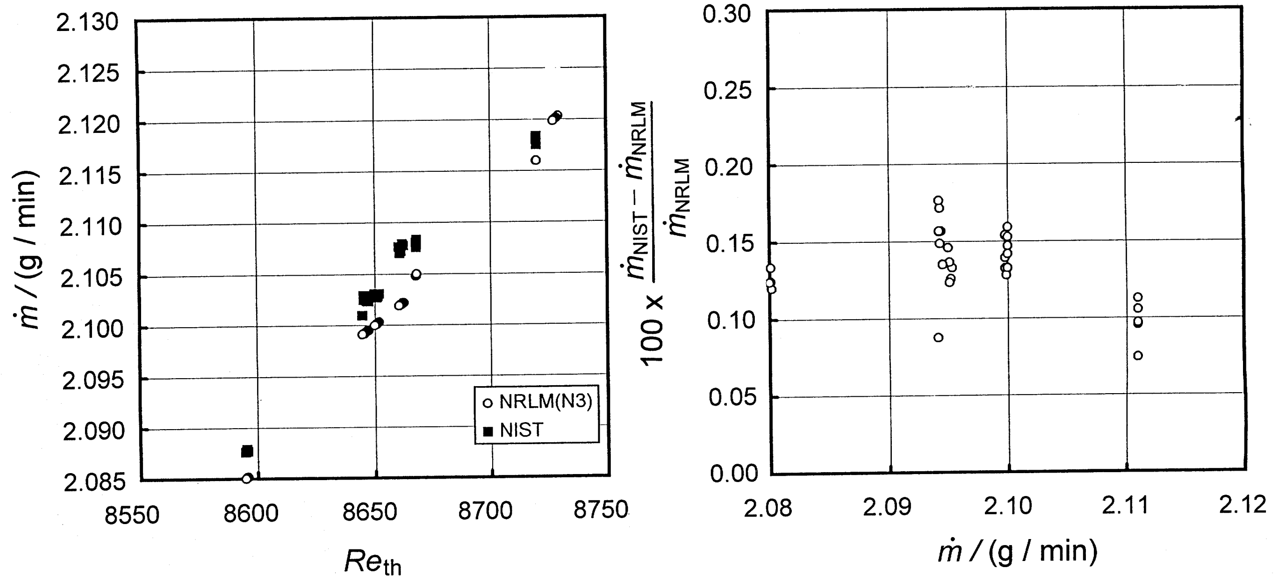


Figure 9. Data from the 2.1 g/min case.

in Figure 6b was used, with a pressure of about 220 kPa upstream of the venturi, and the C_{d} curves for the venturis were extrapolated beyond the range of the original calibration at the NRLM. On return to Japan, the C_{d} values were checked over the range of Reynolds number used during the NIST comparison and the change was found to be negligible (<0.02 %). Calibration checks of the temperature and pressure sensors used in the NRLM transfer standard were also performed on return to Japan and the calibration drift was less than 0.01 % for all of the sensors.

The series flow arrangement allowed the measurements of the NRLM transfer standard and the NIST piston provers to be made over the same time interval for flows greater than 1 g/min. The piston prover provided one flow measurement over a 30 s or more collection interval and the NRLM transfer standard flows (updated every 2 s) were averaged over the piston prover collection interval. A set of five such flow measurements was made for each flow, and each flow was repeated on two or more occasions. Between flow repeats, a change of the sonic venturi in the holder was always made (and consequently the flow brought to zero), and repeats were usually collected on two different days.

7. Results

The results are shown in two different figures for each flow rate, one showing the mass flow rates measured by the piston prover and the NRLM transfer standard versus the NRLM transfer standard theoretical Reynolds number, and the other showing the deviation in percent of the reading (using the NRLM data as the divisor),

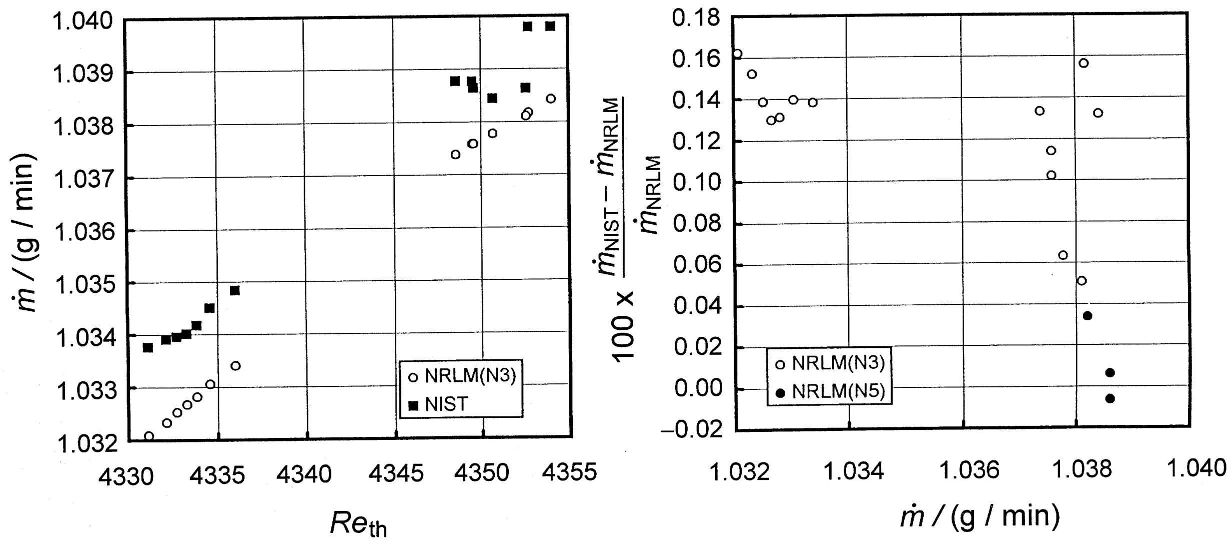


Figure 10. Data from the 1.0 g/min case.

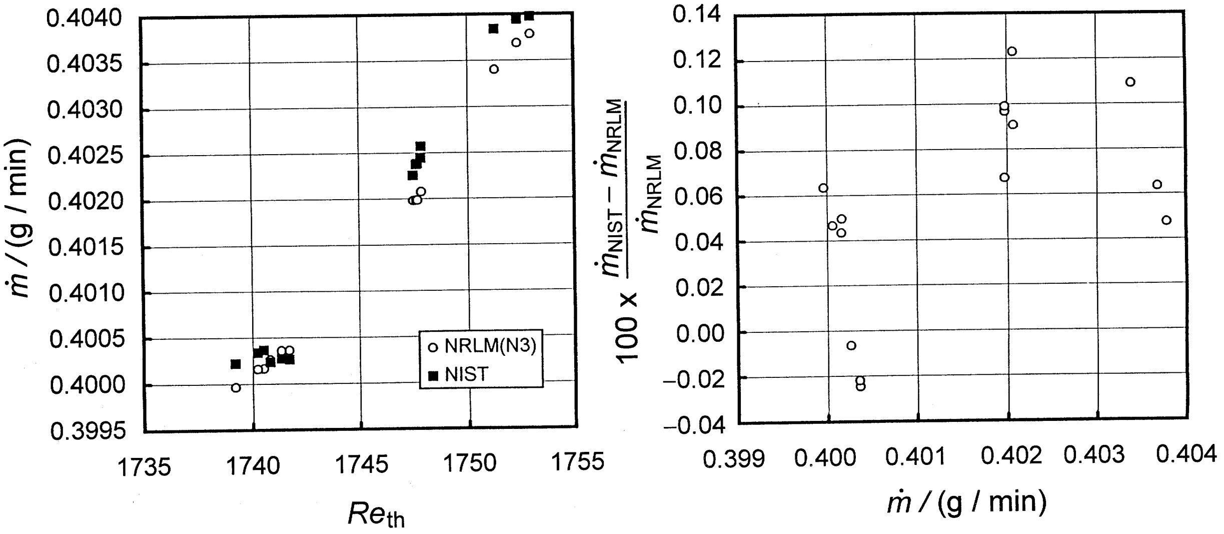


Figure 11. Data from the 0.4 g/min case.

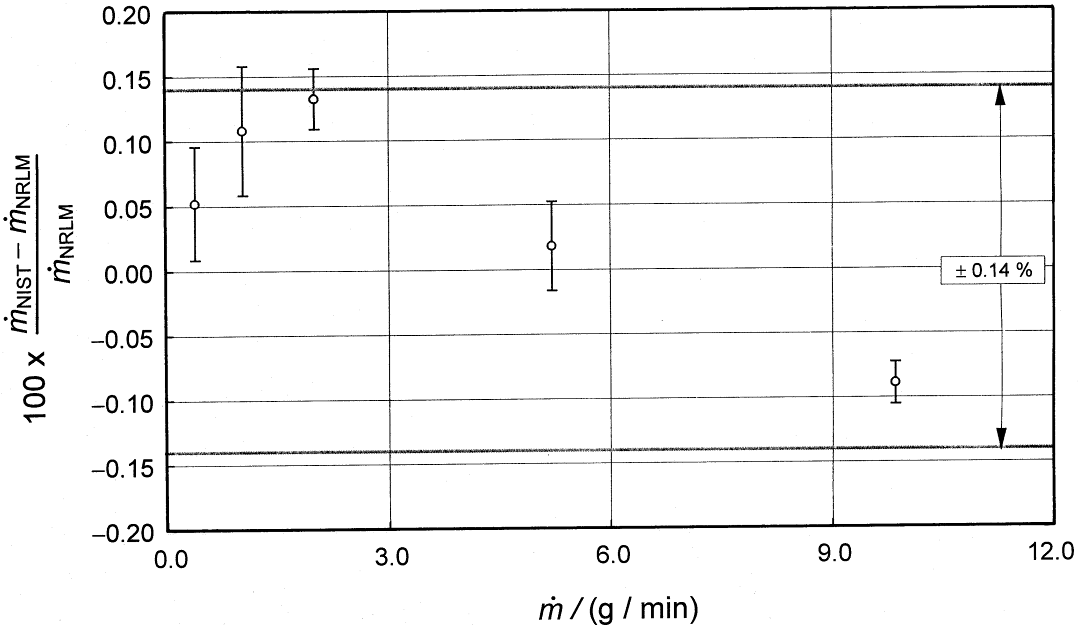


Figure 12. The mean and standard deviation of the percentage differences for each flow rate of the comparison. Also shown is the 67 % confidence uncertainty (±0.14 %) obtained from the root-sum-square of the NRLM transfer standard and NIST piston prover uncertainties.

versus the mass flow rate measured by the transfer standard.

7.1 Case of 11.5 g/min

The results for the highest flow rate tested are shown in Figure 7. The N7 sonic venturi and the large piston prover were used. The deviations between the two flow measuring systems range from –0.07 % to –0.12 %. Two sets of data were collected on two different days.

7.2 Case of 6.0 g/min

The results at 6.0 g/min are shown in Figure 8. The N5 sonic venturi and the largest piston were used to collect three data sets on three different days. The flow measurements show good agreement with deviations of less than 0.10 %.

7.3 Case of 2.1 g/min

The N3 sonic venturi and the medium piston were used to collect the six sets of data presented in Figure 9 which were collected on two different days. Four of the data sets involved switching between the two sets of temperature and pressure sensors available in the NRLM transfer standard while keeping the flow conditions essentially constant and observing what change occurred in the flow measured by the transfer standard. The differences in the flows measured with the two sensor sets was less than 0.02 %. The deviations between the NIST and NRLM flow measurements ranged from 0.07 % to 0.18 %.

7.4 Case of 1.0 g/min

In this case, N3 and N5 were used on different occasions in the parallel arrangement along with the medium piston prover, and four data sets are plotted in Figure 10 (one set contains only two points). The data obtained using N5 are represented by the solid circles in the figure. The deviations between N3 and the piston prover vary from 0.05 % to 0.16 %, but all except two of the points fall between 0.11 % and 0.16 %. The deviations between N5 and the medium piston ranged from –0.01 % to 0.04 %.

7.5 Case of 0.4 g/min

Figure 11 presents the results of the comparison between sonic venturi N3 and the medium piston prover at 0.4 g/min. Three data sets collected on two days are shown (one set contains only three points). Differences between the NRLM transfer standard and the NIST piston prover are less than 0.13 %. The scatter in both this and the previous figure illustrates the increased difficulty of measuring smaller flows, or that greater scatter was introduced by the parallel flow arrangement.

8. Discussion and conclusions

For the individual flow measurements gathered in this comparison (shown in Figures 7 to 11), the deviations ranged from –0.12 % to + 0.18 %. The averages of the data sets at each flow tested are plotted in Figure 12, along with bars representing their standard deviation. The systematic differences between the two flow devices range from –0.09 % to + 0.13 %, while the random differences (the standard deviation) vary between 0.016 % and 0.050 %. One can bound the differences that can be expected when the two flow systems are compared by combining the uncertainties of each (taking the root-sum-of-squares), $[(0.11\ \%)^2 + (0.09\ \%)^2]^{1/2} = 0.14\ \%$. This 0.14 % figure bounds the deviations between the two systems expected during a comparison (at the 67 % level of confidence). The 0.14 % bound is also shown in Figure 12, and one can see that all of the mean deviation points are within this 67 % level of confidence bound. Expanding this uncertainty by a coverage factor of two indicates that with 95 % level of confidence, the deviations between the two facilities should be less than 0.28 %. Therefore, the deviations found during this comparison (which were always less than 0.18 %) show that the uncertainty analyses for the two facilities are reasonable.

There is a concave downward shape to the deviation plot in Figure 12, showing that there are systematic differences between the two facilities that seem to vary with the flow rate. Despite the correlation of the differences with flow rate, however, one cannot rigorously conclude that the differences *are a function of* the flow rate.

The random differences are generally larger for the smaller flow rates. The relative standard deviations are 1.6×10^{-4}, 3.4×10^{-4}, 2.3×10^{-4}, 5.0×10^{-4}, and 4.4×10^{-4} for the 11.5 g/min, 6 g/min, 2.1 g/min, 1.0 g/min, and 0.4 g/min flow rates, respectively. On examining the data sets more closely, it is apparent that the scatter of deviations at each flow rate is often not truly random: there is correlation with time or with the order in which the data points were collected. For some data sets the deviations are generally decreasing with time, while for others they are generally increasing. One explanation for the time correlation is storage effects, i.e. density changes (primarily resulting from temperature changes) in the connecting piping volume. Storage effects would be larger than normal for the parallel test arrangement owing to the single collection method used which does not permit adequate temperature equilibration.

Tests conducted in March 1996 with a laminar flow element [8] and the NIST piston provers showed 0.01 % agreement between the medium and large piston provers at a crossover flow of 1.2 g/min. Therefore, no significant discontinuity is expected in Figure 12 owing to the fact that two different piston provers were used. In fact, the systematic differences appear to be a continuous function of the flow rate, despite the fact that two different provers and three different sonic venturis were used during the comparison. The source of the systematic differences between the NIST Fluid Flow Group piston prover and the NRLM transfer standard is currently unclear, but will be the subject of further investigations by the NIST and the NRLM.

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Nomenclature

A	Throat area
C_d	Discharge coefficient
C^*	Critical flow factor
D	Throat diameter of sonic venturi
P	Pressure
$\dot{m}$	Mass flow rate
$\dot{m}_\ell$	Leakage mass flow rate
$\dot{m}_\mathrm{th}$	Theoretical mass flow rate
Re_th	Theoretical Reynolds number
R	Gas constant
T	Temperature
Z	Compressibility factor
ρ_c	Density of gas in collection volume
$\Delta\rho_\mathrm{a}$	Change in gas density in approach volume
γ	Specific heat ratio
μ	Viscosity of gas
Δt	Collection time
V_c	Collection volume
V_a	Approach volume, volume of connecting piping