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Developing initial set-up for calibrating rotameters and thermal mass flow meters

Xiangwu Tao

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Supervisor: Martin Vilbaste

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Student: Xiangwu Tao

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Abstract:

In this thesis, an easily operable initial measurement system for calibrating rotameters and thermal mass flow meters at flow rates (2…18) L/min is designed. The uncertainties affecting the calibration are also analyzed and the highest contributions are found to be due to the permissible error of the reference gas meter and leakage of the system. These findings provide a direction for further improvement of the measurement system in future.

Abstract(in Estonian):

Käesolevas magistritöös on üles seatud kergesti kasutatav mõõtesüsteem rotameetrite ja soojuslike massivoolumõõturite kalibreerimiseks õhu mahtkiiruse vahemikus (2…18) L/min. Töös analüüsitakse ka kalibreerimist mõjutavaid mõõtemääramatuse allikaid ja leitakse, et suurima panuse annavad referents-gaasiarvesti lubatud viga ja lekked süsteemis. Need tulemused pakuvad juhiseid mõõtesüsteemi edasiseks täiustamiseks tulevikus.

Keywords:

rotameter, thermal mass flow meter, calibration, uncertainty

Keywords(in Estonian):

rotameeter, soojuslik massivoolumõõtur, kalibreerimine, mõõtemääramatus

CERCS code: P180 (Metrology, physical instrumentation)

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Table of Contents

1 Introduction

1.1 Application of gas flow measurement

Gas flow measurement has been an important theme in scientific research and has a wide range of practical applications in life. In 1738, the Swiss physicist Daniel Bernoulli published the *Hydrodynamica*, which greatly contributed to the development of fluid metrology [1]. After the Industrial Revolution, gas flow measurement techniques were gradually improved. Gas flow measurement is used in many applications such as power generation, medical production, environmental protection, for chemical processes and other fields [2]. Currently, popular gas flow measurement technologies include differential pressure flowmeters, rotameters, turbine flowmeters, mass flowmeters, and ultrasonic flowmeters [3].

1.2 Rotameters as flow measuring instruments

Rotameters are widely used to measure flow rates of fluids for industrial applications including chemical engineering, production of pharmaceuticals, light industry and scientific experiments [4]. A rotameter is a conventional variable area flowmeter, typically designed with a vertical conical glass tube with a cross-sectional area that gradually expands from bottom to top, housing a freely rotating rotor (or float) made of metals of various densities [5]. Rotameters have been used in industrial and scientific experiments for more than 150 years [6] and are characterized by reliable performance, simple structure, low price, and easy installation and use.

1.3 Basic principles of a rotameter

The density of the float inside the rotameter must exceed the density of the measured fluid to ensure free vertical movement along the center axis of the tube. Rotameters need to be vertical during operation. In general, readings are taken with the eye at the same level as the maximum cross-sectional area of the internal float. However, some floats are constructed differently and should be read following the manufacturing instructions. The internal float is affected by its gravitational force, air buoyancy force and air drag force, which is related to the dynamic pressure of the air acting on the float. Since the mass and shape of the float are fixed, the gravitational force and air buoyancy force acting on the float remain constant during operation. When the air flow rate increases, the dynamic pressure acting on the float increases, and the float rises. As the float rises, the gap area between the float and the conical tube becomes larger, the dynamic pressure acting on the float decreases until the downward gravitational force and the sum of upward air buoyancy force and drag force on the float are equal, and the float remains stable. The relationship between the forces acting on the float in the rotameter while maintaining its stable position can be written as[7]:

$$F_g = F_b + F_d \qquad (1)$$

where F_g represents the gravitational force, F_b represents the air buoyancy force, and F_d represents the air drag force.

1.4 Rotameter equation

1.4.1 Flow rate calculation equation

The equation for the volume flow rate (Q) of the rotameter is expressed by equation (2) and its derivation is presented in Appendix 1.

$$Q = A_s \sqrt{\frac{2V_{float}g\left(\rho_{float} - \rho_{gas}\right)}{C_d A_f \rho_{gas}}} \qquad (2)\ [5,7]$$

In equation (2):

A_s: the cross-sectional area of the rotameter cone in m^2;

V_{float}: the volume of the float in m^3;

g: the gravitational acceleration in m/s^2;

ρ_{float}: the density of the float in kg/m^3;

ρ_{gas}: the density of the fluid in kg/m^3;

C_d: the air drag coefficient with dimension one;

A_f: the cross-sectional area of the float in m^2.

During the calibration of a rotameter in production, it is typically calibrated using water or air at standard industrial conditions (25°C, 101.3 kPa)[8]. Therefore, in practice, temperature and pressure that characterize fluid density need to be measured if these are different from those during calibration.

1.4.2 Density correction in gas flow rate measurement

The calibration of a rotameter is influenced by the density of the fluid being measured. In the experiment, compressed air flows through the serial connection of the gas meter and rotameter. Under the same mass flow rate assumption (no leaks in the system) the volumetric flow rates of air at the gas meter and rotameter are different due to different gas densities at the two measuring instruments. The relationship between the mass flow rate (Q_m) and the volumetric flow rate (Q) can be expressed as:

$$Q_m = Q \cdot \rho \quad (3)$$

Given that $\rho_{float} \gg \rho_{gas}$, it follows:

$$\rho_{float} - \rho_{gas} \approx \rho_{float} \quad (4)$$

It is known from equation (2) that the values of C_d, A_s, V_{float}, g and A_f are all fixed. Usually, rotameters are calibrated in air at standard conditions. If the rotameter is used to measure the flow rate of some other gas (e.g. oxygen), the relationship between the volumetric flow rates (Q) of the two gases at the same float position of a rotameter can be shown as equation (5) according to equations (2) and (4):

$$\frac{Q_1}{Q_2} = \sqrt{\frac{\rho_2}{\rho_1}} \quad (5)$$

where,

ρ_1: the density of air at standard conditions, measured in kg/m^3;

ρ_2: the density of other gas at standard conditions, measured in kg/m^3.

The density of any gas is related to its pressure and temperature. For a certain amount of gas, it can be described by the ideal gas state equation as (6):

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad (6)$$

Substitution of equation (6) into equation (5), enables to convert the rotameter reading from one set of pressure and temperature to the other:

$$\frac{Q_1}{Q_2} = \sqrt{\frac{P_2}{P_1}}\sqrt{\frac{T_1}{T_2}} \quad (7)$$

where,

P_1, T_1: the pressure and thermodynamic temperature in the first conditions;

P_2, T_2: the pressure and thermodynamic temperature of the gas being measured in the second conditions.

1.5 Thermal mass flow meter

Thermal mass flow meters are mainly used to measure the mass flow rate of gases and are based on the principle of heat transfer [9]. An early thermal mass flow meter was the contact mode thermal flow meter designed by Thomas Edison in the early 20th century [9]. There are two main measurement techniques. The first technique provides a constant input power on a section of device and measures the temperature difference between the two sides of the heated section. This temperature difference is proportional to the mass flow rate of gas. The second technique heats the sensor by maintaining a constant temperature. The power required to maintain a constant temperature is proportional to the mass flow rate of the gas being measured [10]. Unlike volumetric flow meters, thermal mass flow meters are not affected by pressure and temperature variations. It is worth noting that the readings of the thermal mass flow meter are very sensitive to different gases, which can be confirmed in the study of Tison, S. A. [10]. It has been widely used in various industrial fields for gas flow measurement, such as natural gas and coal gas measurement [9].

1.6 Diaphragm gas meter

A diaphragm gas meter is used as the reference measuring instrument to measure gas volume in the experiments described in the thesis. The Diaphragm gas meter originated from a wet-type positive displacement meter invented by Samuel Clegg in 1815. Thomas Glover then invented the two-diaphragm slide valve meter, which is still used today [11]. Diaphragm gas meters are mainly composed of the diaphragm, chamber and measure the volume of gas by counting the number of cycles of emptying and filling the chamber volume [12]. In operation, the gas first enters a chamber under the pressure difference between the inlet and outlet of the instrument, then when the chamber is filled with gas, the diaphragm opens a valve under pressure to allow the gas to enter and fill another chamber and be discharged. Each cycle rotates the measuring piston to accumulate the number of cycles [11].

The relationship between the volumetric flow rates Q_1 and Q_2 determined by gas meter and stopwatch depending on different gas density values in the flow-path under the same mass flow rate condition is presented by equation (8):

$$\frac{Q_1}{Q_2} = \frac{\rho_2}{\rho_1} \quad (8)$$

ρ_1, ρ_2 are the densities of the measured gas at two points of the gas flow-path in kg/m^3.

So if the mass flow rate in the flow path is fixed, the volumetric flow rate measured by a gas meter is inversely proportional to gas density.

1.7 The calibration of measuring instruments

Calibrating measuring instruments is a practice across various industries and laboratories. Calibration enables measuring instruments to provide results close to true values, provided that corrections that are determined during calibration are later on applied to the readings of the measuring instruments.

In general, the true value of the measurand is unknown but the reference value that is the best estimate of the true value is known to us. During calibration process, it is usually necessary to calculate corrections, which can be expressed by the following equation:

$$Correction = R_{reference} - R_{device} \quad (9)$$

where,

$R_{reference}$: the reference value;

R_{device}: the reading of the measuring instrument under calibration.

Once the correction is determined during calibration, it can later be used to calculate corrected values for the measuring instrument:

$$R_{corrected} = R_{device} + Correction \quad (10)$$

where,

$R_{corrected}$: the corrected value of the measuring instrument.

1.8 Different ways of calibrating rotameters

A standard way to calibrate a rotameter is to use a wet test meter or a gasometer [8]. The wet gas test meter (also known as a water-sealed rotating drum meter) works by first introducing gas into a rotating drum that is partially immersed in liquid; the drum begins to rotate as it is filled with the gas and the volume of gas is measured by recording the number of drum rotations. In a gasometer (also known as a bell prover), the flow of gas causes the liquid-sealed, inverted and balanced bell to rise in the vessel containing liquid and gas. The volume of gas flowing into the inverted bell is calculated by the product of rising length of the bell and the inner cross-sectional area of the bell. In both methods, gas is passed through a rotameter controlled by a needle valve and then through either the wet tester or the gasometer. Experimental conditions including room temperature and relative humidity must be recorded. A stopwatch is also used to record the time for a certain volume of gas to pass through a wet test meter or gasometer. The process consists of adjusting the needle valve to achieve the target gas flow rate and then recording a steady rotameter reading.

1.9 GUM method to estimate measurement uncertainty

Measurement uncertainty is a statistical parameter that characterizes the dispersion of quantity values based on the information used. The Guide to the Expression of Uncertainty in Measurement (GUM) is used to estimate measurement uncertainty [13] in this work.
When analyzing experimental data, it is necessary to calculate the output quantity value y from the input quantities x_1 to x_n using the functional relationship f:

$$y = f(x_1, x_2, \ldots, x_n) \quad (11)$$

The next step is to calculate the standard uncertainties for all the input quantities $u(x_i)$. Using the law of propagation of uncertainties, we can calculate the combined standard uncertainty of the measurand $u_c(y)$ [13, 14]:

$$u_c(y) = \sqrt{\sum_{i=1}^{n} \left[\frac{\partial f}{\partial x_i} \cdot u(x_i)\right]^2} \quad (12)$$

where $\frac{\partial f}{\partial x_i}$ is the partial derivative of the measurand with respect to the input quantity x_i [14]. Equation (12) applies for non-correlated input quantities.

Experimental results are usually expressed in terms of expanded uncertainty. The expanded uncertainty provides an interval around the best estimate of the measurement result with a certain level of confidence, usually 95 %. The expanded uncertainty (usually denoted by U) is calculated by multiplying the combined standard uncertainty by the coverage factor (usually denoted by k) using formula (13) [13, 15]:

$$U_y = k \cdot u_c(y) \quad (13)$$

In case of normal distribution and 95 % level of confidence k=2.

1.10 Goals of the thesis

- *Choosing the best set-up for calibration of rotameters and thermal mass flow meters*

The first goal is to design a suitable set-up for the calibration of gas rotameters and thermal mass flow meters in the analytical chemistry department of Tartu University. Experiments will be carried out with two different pre-selected set-ups for calibrating the gas flow meters, and then the most practical calibration set-up will be chosen.

- *Working out the calibration procedure for the best set-up*

The second goal of the thesis is to work out an experimental procedure that enables to calibrate rotameters and thermal mass flow meters at the analytical chemistry department in future.

- *Evaluating uncertainties for the calibration procedure*

The third goal is to provide information on how to estimate measurement uncertainties for the corrections of the flow meters under calibration. All the major uncertainty sources are considered. Part of these uncertainty sources are determined experimentally. Several uncertainty budgets are composed to find out typical uncertainty contributions for two types of flow meters.

2 Experimental set-up

2.1 Setting up the measurement system

Before starting the calibration experiment, two configurations were designed to calibrate the rotameter. These configurations are based on the serial connection of the diaphragm gas meter and gas flow meter under calibration. In general, it is necessary to know air pressure and temperature at the gas meter and the rotameter in order to be able to calculate air densities. Compressed air supplied by the compressed air system of Chemicum is used as the gas to be measured in the experiment. The pressure of the compressed air must be accurately measured, while the small temperature differences have smaller impact on air densities. Therefore, this calibration system requires two vessels that can withstand moderate pressures of compressed air and have good airtightness.

The vessels used in the experiments are cylindrical, about 15 cm in height and 12.5 cm in diameter, made of a ventilation pipe that are covered with two special caps with rubber seals. The seams between the caps and the ventilation pipes are glued with glass adhesive and then taped around the caps to obtain a good airtight seal. Each vessel has been tested for gas airtightness by immersion in water.

Two same-size vessels are used for the experiments. Vessel A has three pre-drilled holes in the caps: two to fix 18 mm copper tubes for air flow and one to fix a 10 mm copper tube for pressure measurements. Vessel B also has three holes in the caps: two to fix 18 and 10 mm copper tubes for air flow and one to fix a 10 mm copper tube for pressure measurements. Each copper tube is fixed to the hole inside the cap by a standard connector and contra-nut. The seams between the standard connectors and the holes inside the caps are sealed with glass adhesive. For pressure measurements, mainly 6 mm plastic tubes together with soft tube connections to manometer are used. 6 mm plastic tubes and quick connectors are also used when connecting rotameter and thermal mass flow meter to the flow path.

The experimental flow path is mainly made up of soft tubing that is attached to the 18 mm copper tubes by special clamps. The inlet and outlet openings of the gas meter are also fitted with 18 mm copper tubes fixed by standard connectors, which can be connected to the soft tubing. The diagrams of the experimental set-ups are shown in Fig.1 and Fig.2:

Figure 1. First configuration

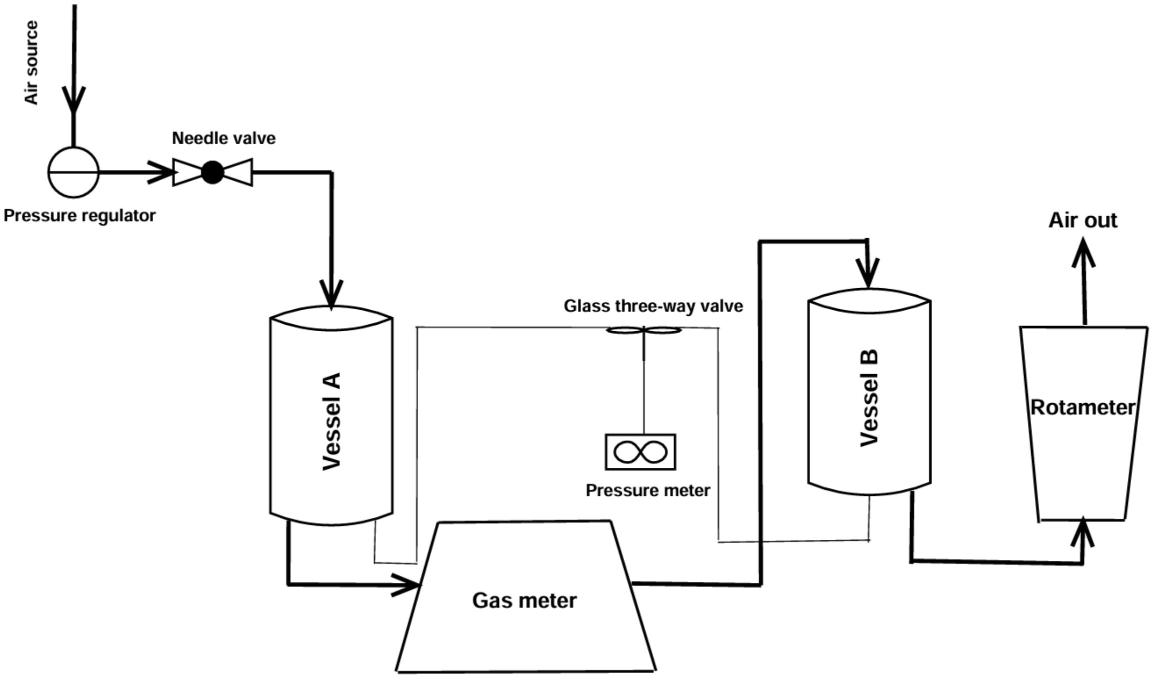
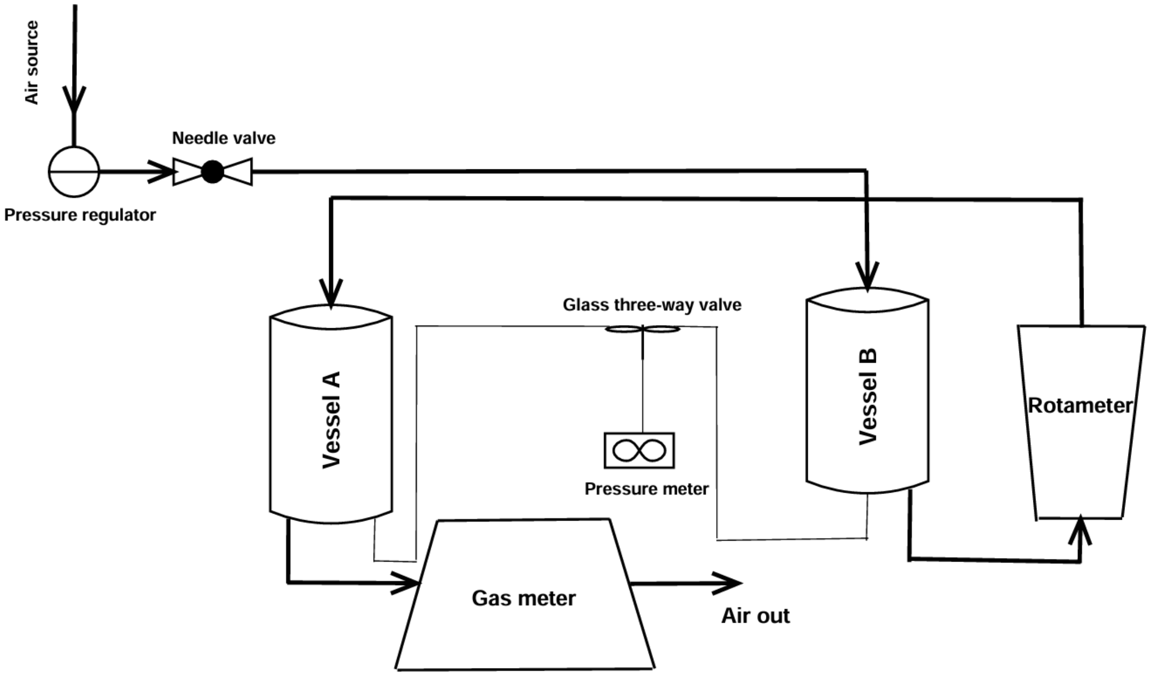


Figure 2. Second configuration



In the experiment to calibrate the thermal mass flow meter, the position of the rotameter in Figures 1 and 2 is replaced by the thermal mass flow meter. The air source is equipped with a pressure regulator and adjustable needle valve to obtain a gas of sufficient flow rate.

As shown in Fig. 1, in the first set-up, the compressed air passes through the serial connection of vessel A, Elster BK-G6T diaphragm gas meter, vessel B, and rotameter or thermal mass flow meter under calibration. In Fig. 2, in the second set-up, the compressed air passes through the serial connection of vessel B, the rotameter or thermal mass flow meter, vessel A, and the gas meter. The soft tubing connections between the instruments are kept as short as possible to minimize air pressure differences. The two vessels and the rotameter (thermal mass flow meter) are fixed on a vertical wooden plate which is supported by two stands.

2.2 Leakage of the measurement system

For experimental set-ups designed to measure gases, it’s important that these are airtight, but some leakage is hardly inevitable in practice. It is assumed that the best estimate for the leak correction R=1 but its uncertainty is not zero.

$$R = 1 - r \quad (14)$$

In the experiment, the relative leakage flow rate r is:

$$r = \left(\frac{Correction_1 - Correction_2}{\frac{Q_{g1} + Q_{g2}}{2}} \right) \cdot 100\% \quad (15)$$

where,

$Correction_1$: the correction value of the rotameter (thermal mass flow meter) in the first set-up;

$Correction_2$: the correction value of the rotameter (thermal mass flow meter) in the second set-up;

Q_{g1}: the gas flow rate through diaphragm gas meter at standard conditions in the first set-up, measured in L/min;

Q_{g2}: the gas flow rate through diaphragm gas meter at standard conditions in the second set-up, measured in L/min.

So, if the rotameter or thermal mass flow meter corrections are equal for both set-ups, it can be assumed that the relative leakage flow rate r is close to zero.

3 Experimental procedures

3.1 Procedure for calibrating a rotameter

As shown in Fig. 1 and Fig. 2, during the experiments, a steady compressed air flow rate is obtained by adjusting the needle valve of the air source, and then the five rotameter readings are recorded when the rotameter float is in a steady position. The volume of compressed air passing through the Elster BK-G6T gas meter is also recorded within the corresponding time (2-3 minutes) while the rotameter readings are recorded.

The gauge pressure inside the vessels at the gas meter and rotameter is measured by a Testo 435 manometer. The rotation of the glass three-way valve enables connecting either vessel A or vessel B to the manometer or pressure sensor. The ambient atmospheric pressure and temperature of the laboratory are measured by the Ahlborn 2290-4 barometer and Pol-Eko RT 2014 2T thermometer. Each set of readings is repeated three times.

3.2 Measurement of pressure drop

In the calibration process, it is necessary to know the air pressure inside the rotameter when the float is stabilized. Since it is not possible to measure the air pressure directly within the instrument, the difference in air pressure between vessel B and the rotameter inlet is measured in the first set-up, so that the air pressure inside the rotameter can be calculated indirectly.

Firstly, the pressure drop between vessel B and the outlet of the rotameter is measured. This pressure drop is equal to the gauge pressure in vessel B in normal calibration mode. Secondly, the tube at the inlet of the rotameter is disconnected and the gauge pressure is again measured in vessel B at the same air flow rate (that is measured by the diaphragm gas meter and stopwatch). The second step of the experiment enables to get information about the pressure drop in the 6 mm tube between vessel B and the inlet of the rotameter. The combination of the two steps enables to calculate the pressure at the inlet of the rotameter and also estimate the pressure inside the rotameter. Measurements are carried out at 5 different air flow rates and each set of readings is repeated three times.

3.3 Influence of tilted position of rotameter on its readings

The rotameter must be used vertically, but some deviations often occur in practice. To increase the reliability of rotameter corrections, the experiment also explores the influence of the tilted position of rotameter on its readings. According to the experimental procedure a protractor is used to mark 0°, 1° and 2° lines relative to the vertical position on the wooden plate, and then the rotameter is aligned according to the 0°, 1° and 2° lines and calibrated according to the measurement procedure as in Section 3.1. The differences between the corrections at 1° and 2° tilt and vertical position (0° tilt) give information about the potential tilt effect that can be taken into account as one uncertainty source for rotameter calibration.

3.4 Procedure for calibrating a thermal mass flow meter

During the experiment, a stable flow rate of compressed air is obtained by adjusting the needle valve of the air source. The stable readings of the thermal mass flow meter are recorded (ten readings) and at the same time, the volume of compressed air that passes through the gas meter within a certain time is measured. The gauge pressure inside the vessels is detected by a pressure sensor connected to the UNI-T UT60BT voltmeter. The glass three-way valve is used to connect either vessel A or vessel B to the pressure sensor. The ambient pressure and temperature of the laboratory are recorded. Each set of readings is repeated three times.

4 Measurement model

4.1.1 The mathematical model for calibrating a rotameter

In the experiment, since the experimental conditions (mainly air pressure and temperature) are different from the standard conditions under which the manufacturer produces the rotameter, it is necessary to convert the flow rate of the rotameter in the experimental conditions to the flow rate under standard conditions to obtain a calibration curve in standardized conditions.

The equation for converting the rotameter's flow rate readings at measuring conditions to flow rate at standard conditions (101325 Pa, 20℃) is:

$$Q_s = (Q_r + Q_{res1})R_T\sqrt{\frac{P_m}{P_{s1}}}\sqrt{\frac{T_{s1}}{T_m}} \quad (16)$$

where,

Q_s: the flow rate of rotameter at standard conditions in L/min;

Q_r: the flow rate reading of rotameter at measuring conditions in L/min;

Q_{res1}: the resolution correction of the rotameter with expected value 0 L/min;

R_T: the correction factor due to tilt effect with expected value 1 (dimensionless);

P_m: the calculated pressure inside rotameter in Pa;

P_{s1}: the standard pressure in Pa;

T_m: the measured temperature at the laboratory, measured in K;

T_{s1}: the standard temperature in K.

In the second set-up, the gas passes through the rotameter first and then through the gas meter. Compared to the first set-up where the gas passes through the gas meter first, the second set-up is more safe, because if the float of the rotameter happens to be blocked, it can easily cause excessive pressure inside the gas meter in the first se-tup (the allowed gauge pressure for the gas meter is 0.5 bar), while in the second setup, since the gas meter is after the rotameter, even if the rotameter becomes blocked, it will not cause excessive pressure inside the gas meter. Therefore, the mathematical model of the second set-up for calibrating the rotameter is preferred. The pressure inside the rotameter (P_m) is calculated by adding ambient pressure to the average gauge pressure difference between the inlet and outlet of the rotameter:

$$P_m = \frac{P_{inlet} - P_{out}}{2} + P_a + \Delta P_{in} + \Delta P_{2.1} \quad (17)$$

$$P_{inlet} = P_{2.2} - P_d \quad (18)$$

$$P_{outlet} = P_{2.2} - P_{2.1} \quad (19)$$

where,

P_{inlet}: the gauge pressure at the inlet of the rotameter, measured in Pa;

P_{out}: the gauge pressure at the outlet of the rotameter, measured in Pa;

P_a: the measured atmospheric pressure in the laboratory in Pa;

ΔP_{in}: the interpretation error for the measurement of pressure inside the rotameter, expressed in Pa. It is estimated as 0 Pa assuming that pressure inside the rotameter is exactly between the inlet and outlet pressure of the rotameter due to the similar construction of the rotameter inlet and outlet connections;

$P_{2.1}$: the gauge pressure measured inside the vessel B in first set-up in Pa;

$\Delta P_{2.1}$: the correction due to the permissible error of the manometer in Pa;

$P_{2.2}$: the gauge pressure measured inside the vessel B in second set-up in Pa;

P_d: the pressure drop between rotameter inlet and vessel B in Pa.

In a similar way, the equation for converting a gas meter's flow rate at measuring conditions to the flow rate at standard conditions is:

$$Q_1 = \frac{V}{t} \frac{T_{s1}}{T_m} \frac{P_{g1}}{P_{s1}} R_l \quad (20)$$

where,

Q_1: the flow rate of gas meter at rotameter standard conditions in L/min;

V: the volume of gas passed through the gas meter, measured in L;

t: the time of recording the volume of gas passing through the gas meter, measured in min;

R_l: dimensionless leak correction with expected value 1;

P_{g1}: the calculated pressure at gas meter in Pa that can be calculated by the following equation:

$$P_{g1} = P_1 + \Delta P_1 + P_a \quad (21)$$

where:

P_1: the gauge pressure inside the vessel A in Pa;

ΔP_1: the correction due to the permissible error of the manometer in Pa.

By substituting equations (16)-(21) into the correction equation for the second set-up it is possible to reach equation (22):

$$Correction = \frac{T_{s1}(P_1 + P_a + \Delta P_1)VR_l}{T_m P_{s1} t} - (Q_r + Q_{res1})R_T \sqrt{\frac{(P_{2.1} - P_d + 2P_a + 2\Delta P_{in} + 2\Delta P_{2.1})T_{s1}}{2P_{s1}T_m}} \quad (22)$$

4.1.2 The uncertainties of input quantities in a rotameter calibration model

Table 1 shows the main sources of uncertainty in calibrating the rotameter as obtained from model (22):

Table 1. Uncertainty sources in calibrating the rotameter

Quantity	Symbol	Unit	Distribution
the reference temperature standard uncertainty with value 0 K	$u_{(Ts1)}$	K	rectangular
the uncertainty due to the repeatability of gauge pressure measurements inside vessel A based on standard deviation	$u_{(P1)}$	Pa	normal
the uncertainty due to the permissible error of the barometer (±500 Pa)	$u_{(Pa)}$	Pa	rectangular
the uncertainty due to the permissible error of the manometer (±1 % of reading or 2 Pa, whichever is greater)	$u_{(\Delta P1)}$	Pa	rectangular
the uncertainty due to the permissible error of the diaphragm gas meter based on information of the manufacturer (±1.5 %)	$u_{(V)}$	L	rectangular
the uncertainty of temperature measurements in the laboratory with half-width of limits 1 K	$u_{(Tm)}$	K	rectangular
the reference atmospheric pressure standard uncertainty with value 0 Pa	$u_{(Ps1)}$	Pa	rectangular
the uncertainty of time measurements based on estimated reaction time 0.3 s	$u_{(t)}$	min	rectangular
the uncertainty due to repeatability of rotameter readings based on standard deviation of repeated measurements	$u_{(Qr)}$	L/min	normal
the uncertainty due to resolution of rotameter based on mentally dividing the lowest scale division into five parts	$u_{(Qres1)}$	L/min	rectangular
the uncertainty of correction factor due to tilt effect based on special experiments (± 0.006)	$u_{(RT)}$		rectangular
the uncertainty due to repeatability of gauge pressure measurements inside vessel B in the first set-up based on standard deviation of repeated measurements	$u_{(P2.1)}$	Pa	normal
the uncertainty due to permissible error of the manometer based on information from the manufacturer	$u_{(Pd)}$	Pa	rectangular
the interpretation uncertainty of pressure inside the rotameter (±5 % of the pressure difference between rotameter inlet and outlet)	$u_{(\Delta Pin)}$	Pa	rectangular
the uncertainty due to the permissible error of the manometer for pressure inside vessel B in first set-up (±1 % of reading or 2 Pa, whichever is greater)	$u_{(\Delta P2.1)}$	Pa	rectangular
the uncertainty due to leak correction	$u_{(Rl)}$		rectangular

4.2.1 The mathematical model for calibrating a thermal mass flow meter

Due to the fact that the thermal mass flow meter readings are almost independent of the changes in pressure and temperature, there is no need to make additional corrections for pressure and temperature as in the case of the rotameter. So the flow rate in normal liters per minute is measured experimentally by taking the average of ten repeated measurements.

Similarly to the experiments with rotameter, the gas flow rate in the flow-path can be estimated. This process involves recording the gas volume and time it takes to pass through the gas meter when the thermal mass flow meter reading is stable. The equation can be written as:

$$Q_T = \frac{V}{t}\frac{T_{s2}}{T_m}\frac{P_{g2}}{P_{s2}} \cdot R_l \quad (23)$$

where,

Q_T: the gas meter reading converted to normal conditions (P_{s2}= 1 atm, T_{s2}=273.15 K), measured in L/min;

P_{g2}: the calculated pressure at gas meter in Pa.

In the experiments, the air pressure (P_{g2}) at the gas meter is measured by using a differential pressure sensor Amphenol ELVH-B001D-HNND-C-NAA4A together with voltmeter because gauge pressures in the vessels exceed the measurement range of the Testo 435 digital manometer. The linear relationship between voltage and pressure is first calculated according to pressure sensor datasheet and then the slope (*S*) and intercept (*C*) of this linear relationship are obtained. The pressure at the gas meter can be expressed by the following equation:

$$P_{g2} = \frac{V_m + \Delta V_m - C}{S} \cdot 100000 + \Delta P_s + P_a \quad (24)$$

where,

V_m: the measured voltage over the pressure sensor in V;

ΔV_m: the permissible error of the voltmeter in V;

ΔPs: the permissible error of the pressure sensor in Pa.

By combining equations (23) and (24), the correction value for the thermal mass flow meter can be obtained:

$$Correction = (\frac{[(V_m + \Delta V_m - C) \cdot 100000 + \Delta P_s S + P_a S] V T_{s2}}{T_m P_{s2} S t}) \cdot R_l - (Q_d + Q_{res2}) (25)$$

where,

Q_d: the average of ten readings of the thermal mass flow meter, measured in normal liters per minute (nL/min);

Q_{res2}: the resolution of the thermal mass flow meter in nL/min.

4.2.2 The uncertainties of input quantities in a thermal mass flow meter calibration model

Table 2 shows the main sources of uncertainty in calibrating the thermal mass flow meter as obtained from model (25):

Table 2. Uncertainty sources in calibrating the thermal mass flow meter

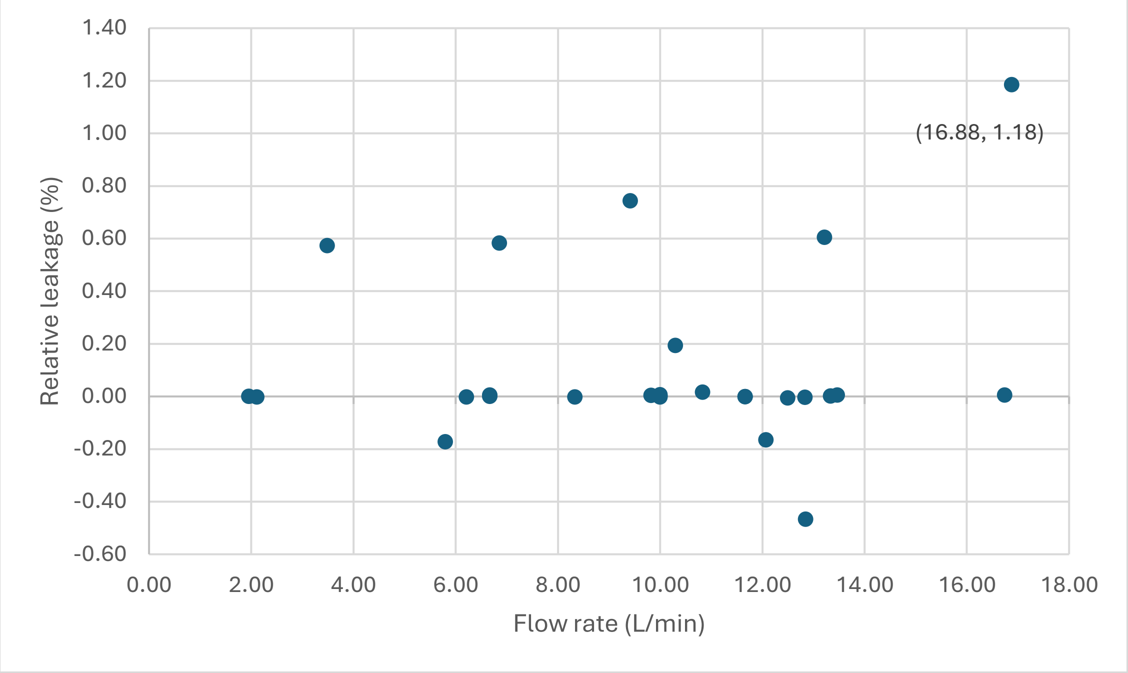
Quantity	Symbol	Unit	Distribution
the uncertainty due to the permissible error of the voltmeter	$u_{(Vm)}$	V	rectangular
the uncertainty due to the accuracy of the voltmeter	$u_{(\Delta Vm)}$	V	rectangular
the uncertainty of intercept of the voltage to pressure relationship according to manufacturer datasheet	$u_{(C)}$	V	rectangular
the uncertainty of slope of the voltage to pressure relationship according to manufacturer datasheet	$u_{(S)}$	V/Pa	rectangular
the uncertainty due to the permissible error of the pressure sensor	$u_{(\Delta Ps)}$	Pa	rectangular
the uncertainty due to the permissible error of the barometer (±500 Pa)	$u_{(Pa)}$	Pa	rectangular
the uncertainty due to the permissible error of the diaphragm gas meter based on information of the manufacturer (±1.5 %)	$u_{(V)}$	L	rectangular
the reference temperature standard uncertainty with value 0 K	$u_{(Ts2)}$	K	rectangular
the uncertainty of temperature measurements in the laboratory with half-width of limits 1 K	$u_{(Tm)}$	K	rectangular
the reference atmospheric pressure standard uncertainty with value 0 Pa	$u_{(Ps2)}$	Pa	rectangular
the uncertainty of time measurements based on estimated reaction time 0.3 s	$u_{(t)}$	min	rectangular
the uncertainty due to repeatability of thermal mass flow meter readings based on standard deviation of repeated measurements	$u_{(Qd)}$	L/min	normal
the uncertainty due to resolution of thermal mass flow meter	$u_{(Qres2)}$	L/min	rectangular
the uncertainty due to leak correction	$u_{(Rl)}$		rectangular

5 Results and discussion

5.1 Airtightness of the whole set-up

Experiments are performed for the same air flow rates using the first and second set-ups. After that calculations are made according to equation (15) to obtain the relative leakage of the whole set-ups. On Figure 3 relative leakage depending on air flow rate is presented.

Figure 3. The experimental data about relative leakage and air flow rate



On Figure 3 it can be seen that the relative leakage in the worst case is just over 1% at air flow rate 16.88 L/min (1.18%). This can be considered to be acceptable. It can even be true that the leak flow rates at lower and medium air flow rates are close to zero based on the distribution of relative leak values.

The negative leak flow rates on Figure 3 are probably caused by random effects while calibrating the flow meters. In principle, negative leak flow rates are not possible if there is overpressure in the flow path.

5.2 The results of the pressure drop measurements

Figure 4 shows the relationship between flow rates and pressure drops due to the 6 mm tube connecting vessel B and the rotameter inlet:

Figure 4. The relationship between flow rate and pressure drop

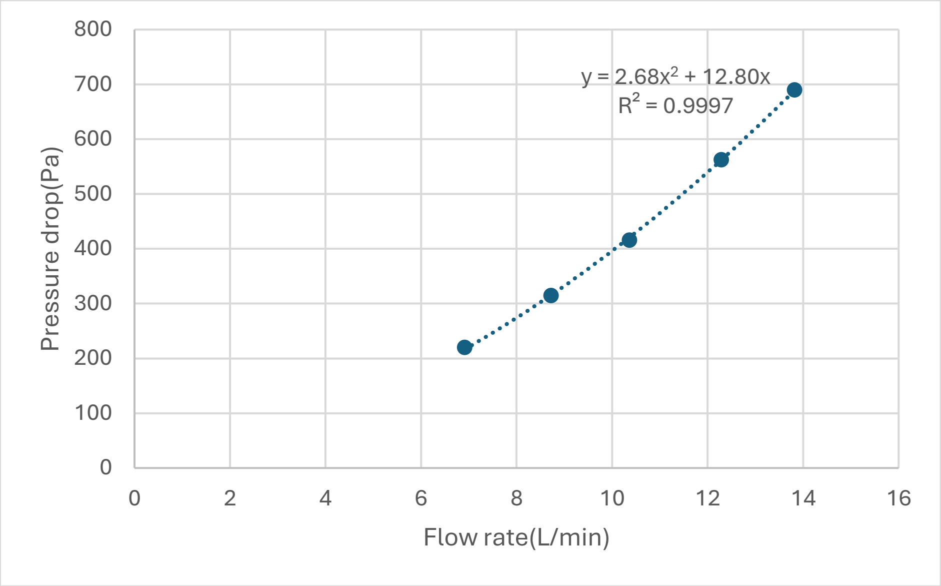


Figure 4 shows that the flow rate dependence of pressure drop in the tube is slightly non-linear that can be approximated by model $y = 2.68x^2 + 12.80x$ where *x* stands for flow rate measured in diaphragm gas meter and *y* stands for pressure drop.

5.3 Analyzing the effect of tilt on rotameter readings

Table 3 shows the relative errors of rotameter readings when the rotameter is tilted at 1° and 2° with respect to the vertical position (0 °):

Table 3. Rotameter relative error for 1° and 2° tilt

Rotameter reading(L/h)	Tilt 1°	Tilt 2°
200	-0.87%	-0.78%
400	-0.16%	-1.70%
600	-0.49%	-2.29%
700	-0.71%	-1.93%
750	-0.83%	-1.65%

In practice, the rotameter is usually not tilted more than 1°. The calculated average error for 1° tilt is -0.61%. This value is included in the uncertainty estimation.

5.4 The results of calibrating a rotameter

5.4.1 Calibration results

Tables 4 and 5 show the rotameter corrections at different air flow rates:

Table 4. The corrections of the rotameter in the first set-up

Calculated flow rate in Diaphragm gas meter (L/min)	Rotameter reading (L/min)	Rotameter corrections (L/min)	Expanded uncertainty (L/min)
3.51	3.37	0.14	0.09
6.87	6.70	0.17	0.16
10.31	10.06	0.25	0.24
12.06	11.75	0.31	0.28
12.82	12.61	0.21	0.30

Table 5. The corrections of the rotameter in the second set-up

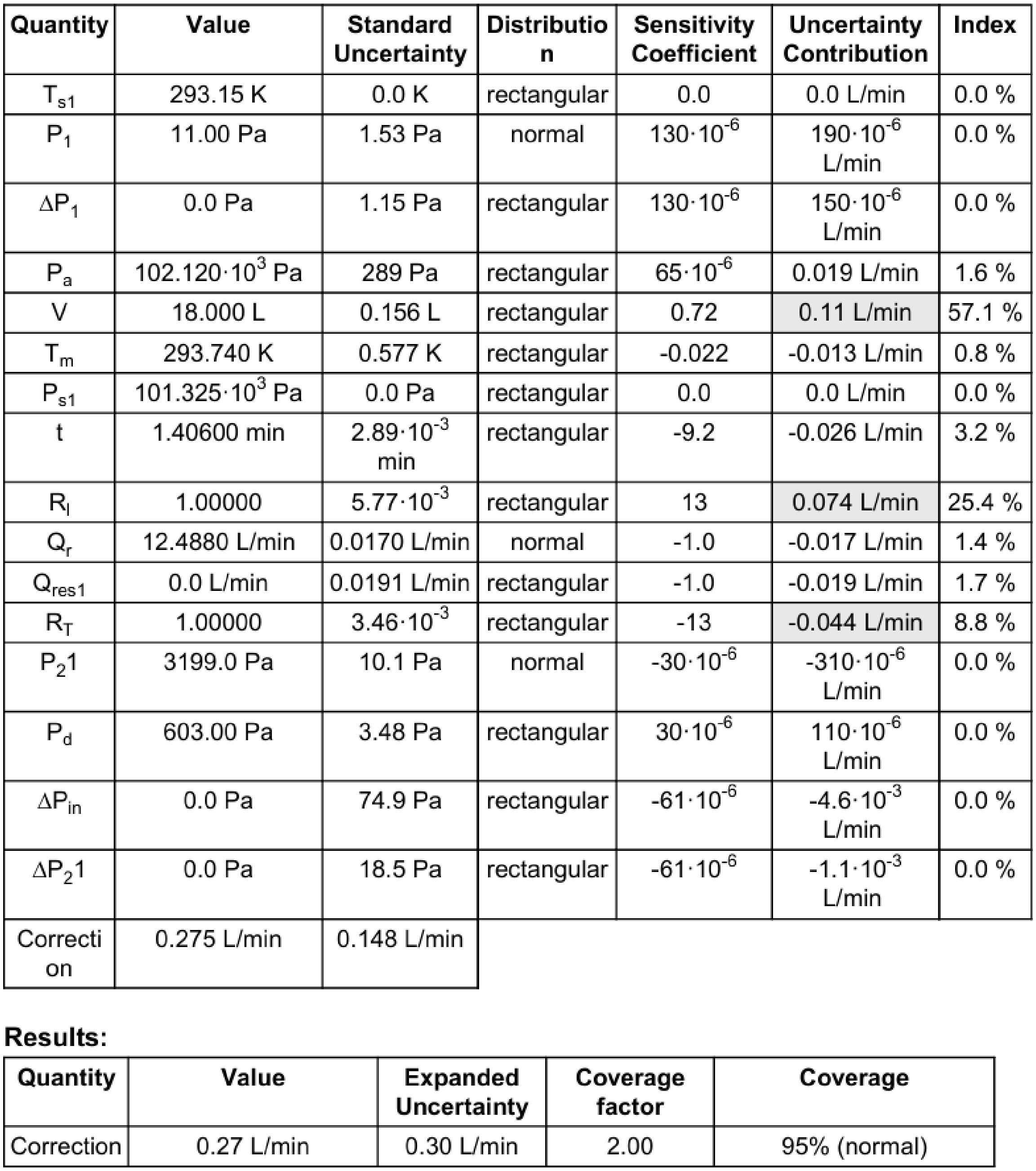
Calculated flow rate in Diaphragm gas meter (L/min)	Rotameter reading (L/min)	Rotameter corrections (L/min)	Expanded uncertainty (L/min)
3.47	3.35	0.12	0.09
6.84	6.71	0.13	0.16
10.29	10.06	0.23	0.24
12.08	11.75	0.33	0.28
12.88	12.61	0.27	0.30

Tables 4 and 5 show positive corrections for the rotameter under study.

5.4.2 The uncertainty budgets for calibrating a rotameter

In order to have a more realistic assessment of the performance and reliability of the flowmeter under operating conditions, in this study uncertainties at low and high flow rates are estimated. Tables 6 and 7 show the uncertainty budgets at a high flow rate (750 L/h) and low flow rate (200 L/h), respectively:

Table 6. The uncertainty budget for rotameter correction at 750 L/h based on GUM Workbench 2.3 software

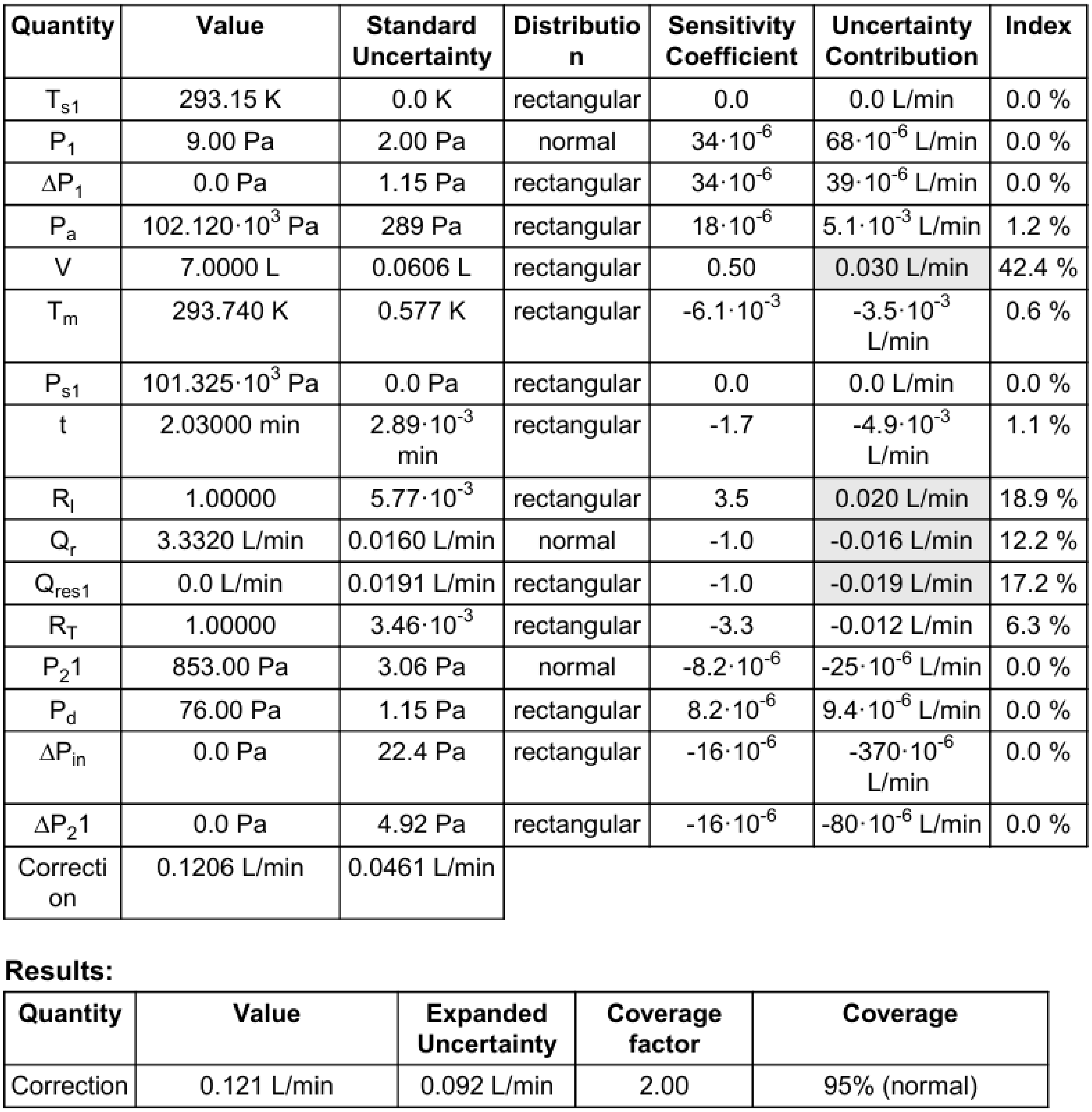


Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
T_{s1}	293.15 K	0.0 K	rectangular	0.0	0.0 L/min	0.0 %
P_1	11.00 Pa	1.53 Pa	normal	$130\cdot10^{-6}$	$190\cdot10^{-6}$ L/min	0.0 %
ΔP_1	0.0 Pa	1.15 Pa	rectangular	$130\cdot10^{-6}$	$150\cdot10^{-6}$ L/min	0.0 %
P_a	$102.120\cdot10^{3}$ Pa	289 Pa	rectangular	$65\cdot10^{-6}$	0.019 L/min	1.6 %
V	18.000 L	0.156 L	rectangular	0.72	0.11 L/min	57.1 %
T_m	293.740 K	0.577 K	rectangular	-0.022	-0.013 L/min	0.8 %
P_{s1}	$101.325\cdot10^{3}$ Pa	0.0 Pa	rectangular	0.0	0.0 L/min	0.0 %
t	1.40600 min	$2.89\cdot10^{-3}$ min	rectangular	-9.2	-0.026 L/min	3.2 %
R_l	1.00000	$5.77\cdot10^{-3}$	rectangular	13	0.074 L/min	25.4 %
Q_r	12.4880 L/min	0.0170 L/min	normal	-1.0	-0.017 L/min	1.4 %
Q_{res1}	0.0 L/min	0.0191 L/min	rectangular	-1.0	-0.019 L/min	1.7 %
R_T	1.00000	$3.46\cdot10^{-3}$	rectangular	-13	-0.044 L/min	8.8 %
P_21	3199.0 Pa	10.1 Pa	normal	$-30\cdot10^{-6}$	$-310\cdot10^{-6}$ L/min	0.0 %
P_d	603.00 Pa	3.48 Pa	rectangular	$30\cdot10^{-6}$	$110\cdot10^{-6}$ L/min	0.0 %
ΔP_{in}	0.0 Pa	74.9 Pa	rectangular	$-61\cdot10^{-6}$	$-4.6\cdot10^{-3}$ L/min	0.0 %
ΔP_21	0.0 Pa	18.5 Pa	rectangular	$-61\cdot10^{-6}$	$-1.1\cdot10^{-3}$ L/min	0.0 %
Correction	0.275 L/min	0.148 L/min				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
Correction	0.27 L/min	0.30 L/min	2.00	95% (normal)

Table 7. The uncertainty budget for rotameter correction at 200 L/h based on GUM Workbench 2.3 software



Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
T_{s1}	293.15 K	0.0 K	rectangular	0.0	0.0 L/min	0.0 %
P_1	9.00 Pa	2.00 Pa	normal	$34\cdot10^{-6}$	$68\cdot10^{-6}$ L/min	0.0 %
ΔP_1	0.0 Pa	1.15 Pa	rectangular	$34\cdot10^{-6}$	$39\cdot10^{-6}$ L/min	0.0 %
P_a	$102.120\cdot10^{3}$ Pa	289 Pa	rectangular	$18\cdot10^{-6}$	$5.1\cdot10^{-3}$ L/min	1.2 %
V	7.0000 L	0.0606 L	rectangular	0.50	0.030 L/min	42.4 %
T_m	293.740 K	0.577 K	rectangular	$-6.1\cdot10^{-3}$	$-3.5\cdot10^{-3}$ L/min	0.6 %
P_{s1}	$101.325\cdot10^{3}$ Pa	0.0 Pa	rectangular	0.0	0.0 L/min	0.0 %
t	2.03000 min	$2.89\cdot10^{-3}$ min	rectangular	-1.7	$-4.9\cdot10^{-3}$ L/min	1.1 %
R_l	1.00000	$5.77\cdot10^{-3}$	rectangular	3.5	0.020 L/min	18.9 %
Q_r	3.3320 L/min	0.0160 L/min	normal	-1.0	-0.016 L/min	12.2 %
Q_{res1}	0.0 L/min	0.0191 L/min	rectangular	-1.0	-0.019 L/min	17.2 %
R_T	1.00000	$3.46\cdot10^{-3}$	rectangular	-3.3	-0.012 L/min	6.3 %
$P_2 1$	853.00 Pa	3.06 Pa	normal	$-8.2\cdot10^{-6}$	$-25\cdot10^{-6}$ L/min	0.0 %
P_d	76.00 Pa	1.15 Pa	rectangular	$8.2\cdot10^{-6}$	$9.4\cdot10^{-6}$ L/min	0.0 %
ΔP_{in}	0.0 Pa	22.4 Pa	rectangular	$-16\cdot10^{-6}$	$-370\cdot10^{-6}$ L/min	0.0 %
$\Delta P_2 1$	0.0 Pa	4.92 Pa	rectangular	$-16\cdot10^{-6}$	$-80\cdot10^{-6}$ L/min	0.0 %
Correction	0.1206 L/min	0.0461 L/min				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
Correction	0.121 L/min	0.092 L/min	2.00	95% (normal)

Table 6 shows that the main uncertainty factors affecting the high flow rate calibration are the volume measurement by the diaphragm gas meter (57.1%), the correction factor due to the leakage effect (25.4%) and the correction factor due to the tilt effect (8.8%). According to Table 7, the main uncertainties affecting the low flow rate calibration come from the volume measurement by the diaphragm gas meter (42.4%), the correction factor due to the leakage effect (18.9%), resolution of rotameter (17.2%) and the repeatability of the rotameter readings (12.2%).

Inaccuracy in gas meter volume measurements can be improved by regular calibration of the diaphragm gas meter with expanded uncertainty significantly lower than the permissible error of the gas meter and averaging multiple measurements.

In order to minimize the effects of leakage, in addition to making the flow path connections as short as possible, it is recommended to design more gas-tight vessels so that less gas leaks out of the vessels at higher gauge pressures. To minimize the effects of tilt, it is recommended from time to time to use a carpenter’s level to check the vertical position of the rotameter under calibration.

In order to minimize the impact of the readings, the readings should be taken correctly and the line of sight should be at the same level as the float cross-section; it is also recommended to install a mass flow controller in the flow path before the gas flow meter and rotameter, in order to reduce air flow instability.

5.5 The result of calibrating a thermal mass flow meter

5.5.1 Calibration result

Tables 8 and 9 show the thermal mass flow meter corrections at different air flow rates:

Table 8. The corrections of the thermal mass flow meter in the first set-up

Calculated flow rate in Diaphragm gas meter (L/min)	Thermal mass flow meter reading (L/min)	Thermal mass flow meter corrections (L/min)	Expanded uncertainty (L/min)
1.97	2.05	-0.08	0.05
5.81	6.01	-0.20	0.16
9.49	10.04	-0.55	0.27
13.24	14.02	-0.78	0.33
16.97	17.93	-0.96	0.40

Table 9. The corrections of the thermal mass flow meter in the second set-up

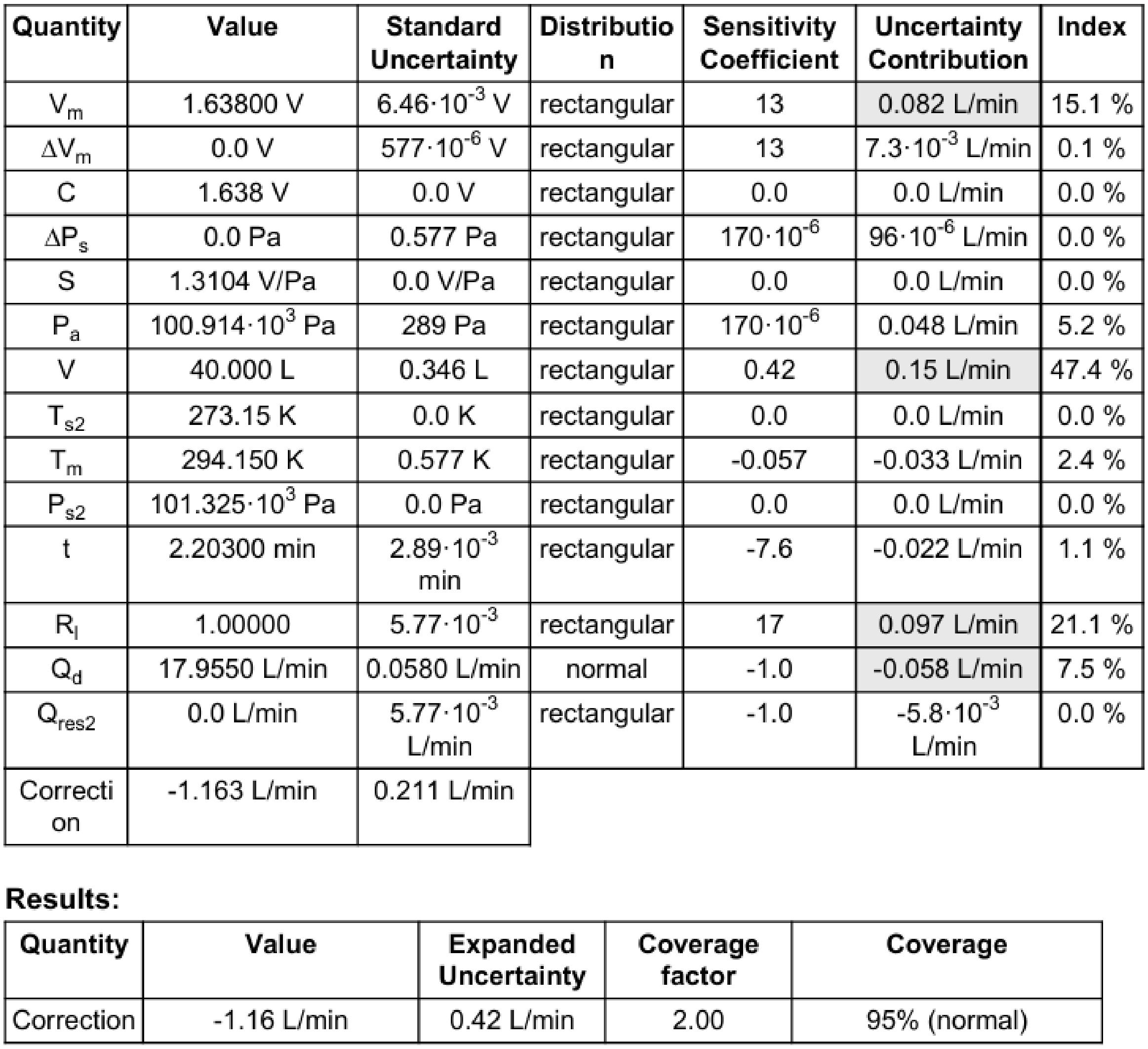
Calculated flow rate in Diaphragm gas meter(L/min)	Thermal mass flow meter reading (L/min)	Thermal mass flow meter corrections (L/min)	Expanded uncertainty (L/min)
1.94	2.02	-0.08	0.05
5.79	5.98	-0.19	0.17
9.35	9.97	-0.62	0.24
13.20	14.06	-0.86	0.32
16.79	17.95	-1.16	0.42

Tables 8 and 9 show negative corrections for the thermal mass flow meter under study.

5.5.2 The uncertainty budgets for calibrating a thermal mass flow meter

Similar to the rotameter calibration process, low and high flow rates are also chosen for the thermal mass flow meter calibration to assess the effect of uncertainties on the calibration. Tables 10 and 11 show the uncertainty budgets at a high flow rate (18 L/min) and low flow rate (2 L/min), respectively:

Table 10. The uncertainty budget for thermal mass flow meter correction at 18 L/min based on GUM Workbench 2.3 software

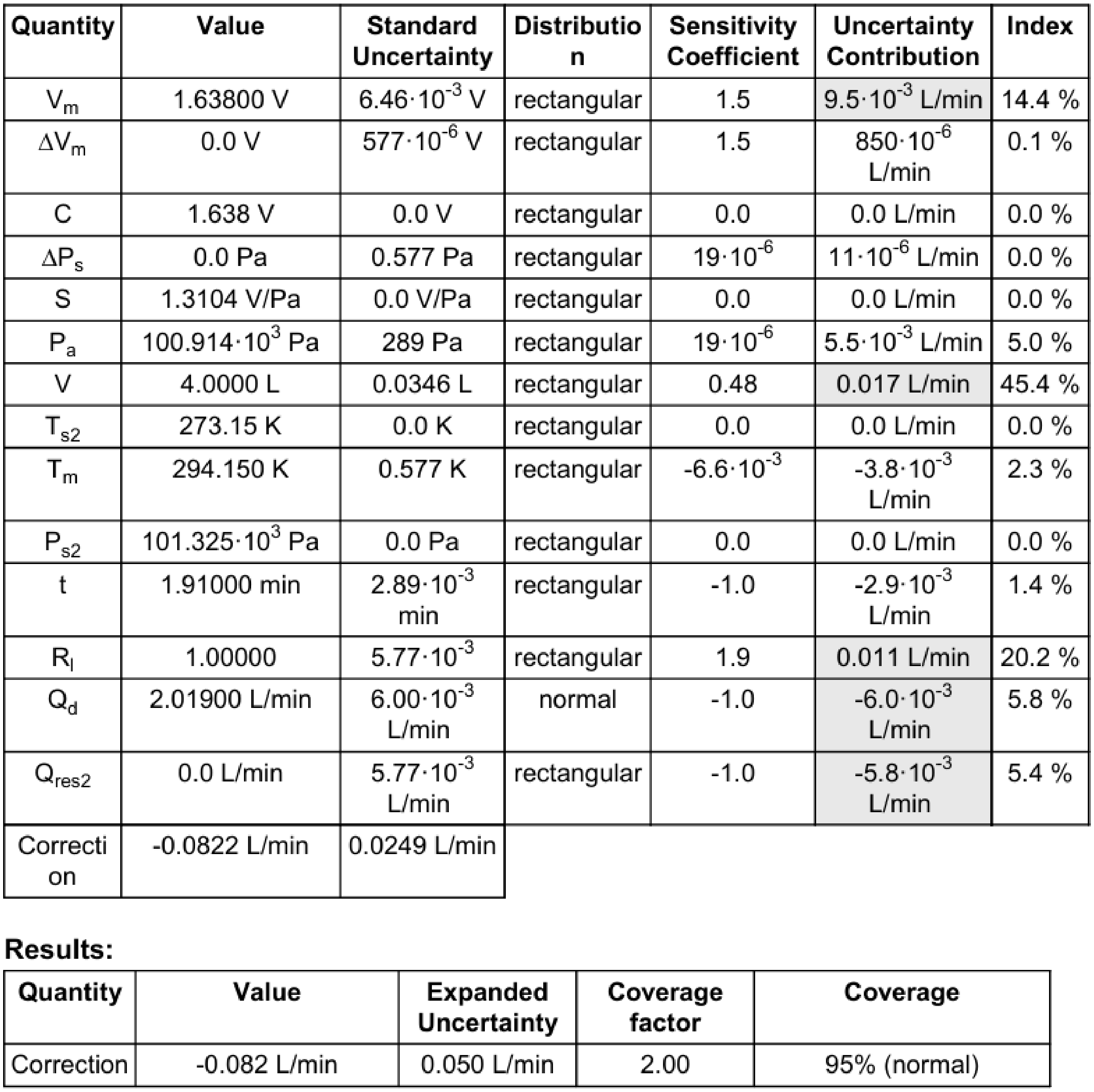


Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
V_m	1.63800 V	$6.46\cdot10^{-3}$ V	rectangular	13	0.082 L/min	15.1 %
ΔV_m	0.0 V	$577\cdot10^{-6}$ V	rectangular	13	$7.3\cdot10^{-3}$ L/min	0.1 %
C	1.638 V	0.0 V	rectangular	0.0	0.0 L/min	0.0 %
ΔP_s	0.0 Pa	0.577 Pa	rectangular	$170\cdot10^{-6}$	$96\cdot10^{-6}$ L/min	0.0 %
S	1.3104 V/Pa	0.0 V/Pa	rectangular	0.0	0.0 L/min	0.0 %
P_a	$100.914\cdot10^{3}$ Pa	289 Pa	rectangular	$170\cdot10^{-6}$	0.048 L/min	5.2 %
V	40.000 L	0.346 L	rectangular	0.42	0.15 L/min	47.4 %
T_{s2}	273.15 K	0.0 K	rectangular	0.0	0.0 L/min	0.0 %
T_m	294.150 K	0.577 K	rectangular	-0.057	-0.033 L/min	2.4 %
P_{s2}	$101.325\cdot10^{3}$ Pa	0.0 Pa	rectangular	0.0	0.0 L/min	0.0 %
t	2.20300 min	$2.89\cdot10^{-3}$ min	rectangular	-7.6	-0.022 L/min	1.1 %
R_l	1.00000	$5.77\cdot10^{-3}$	rectangular	17	0.097 L/min	21.1 %
Q_d	17.9550 L/min	0.0580 L/min	normal	-1.0	-0.058 L/min	7.5 %
Q_{res2}	0.0 L/min	$5.77\cdot10^{-3}$ L/min	rectangular	-1.0	$-5.8\cdot10^{-3}$ L/min	0.0 %
Correction	-1.163 L/min	0.211 L/min				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
Correction	-1.16 L/min	0.42 L/min	2.00	95% (normal)

Table 11. The uncertainty budget for thermal mass flow meter correction at 2 L/min based on GUM Workbench 2.3 software



Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
V_m	1.63800 V	$6.46 \cdot 10^{-3}$ V	rectangular	1.5	$9.5 \cdot 10^{-3}$ L/min	14.4 %
ΔV_m	0.0 V	$577 \cdot 10^{-6}$ V	rectangular	1.5	$850 \cdot 10^{-6}$ L/min	0.1 %
C	1.638 V	0.0 V	rectangular	0.0	0.0 L/min	0.0 %
ΔP_s	0.0 Pa	0.577 Pa	rectangular	$19 \cdot 10^{-6}$	$11 \cdot 10^{-6}$ L/min	0.0 %
S	1.3104 V/Pa	0.0 V/Pa	rectangular	0.0	0.0 L/min	0.0 %
P_a	$100.914 \cdot 10^{3}$ Pa	289 Pa	rectangular	$19 \cdot 10^{-6}$	$5.5 \cdot 10^{-3}$ L/min	5.0 %
V	4.0000 L	0.0346 L	rectangular	0.48	0.017 L/min	45.4 %
T_{s2}	273.15 K	0.0 K	rectangular	0.0	0.0 L/min	0.0 %
T_m	294.150 K	0.577 K	rectangular	$-6.6 \cdot 10^{-3}$	$-3.8 \cdot 10^{-3}$ L/min	2.3 %
P_{s2}	$101.325 \cdot 10^{3}$ Pa	0.0 Pa	rectangular	0.0	0.0 L/min	0.0 %
t	1.91000 min	$2.89 \cdot 10^{-3}$ min	rectangular	-1.0	$-2.9 \cdot 10^{-3}$ L/min	1.4 %
R_l	1.00000	$5.77 \cdot 10^{-3}$	rectangular	1.9	0.011 L/min	20.2 %
Q_d	2.01900 L/min	$6.00 \cdot 10^{-3}$ L/min	normal	-1.0	$-6.0 \cdot 10^{-3}$ L/min	5.8 %
Q_{res2}	0.0 L/min	$5.77 \cdot 10^{-3}$ L/min	rectangular	-1.0	$-5.8 \cdot 10^{-3}$ L/min	5.4 %
Correction	-0.0822 L/min	0.0249 L/min				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
Correction	-0.082 L/min	0.050 L/min	2.00	95% (normal)

Tables 10 and 11 show that the main uncertainty sources affecting the high flow rate thermal mass flow meter calibration are the volume measurement by the diaphragm gas meter (47.4%), the correction factor due to the leakage effect (21.1%), the voltage measurement by the voltmeter (15.1%) and the repeatability of the thermal mass flow meter readings(7.5%), while the main uncertainties affecting the low flow rate calibration come from the resolution of the thermal mass flow meter (5.4%) in addition to the above mentioned input quantities. The voltmeter can be calibrated regularly to reduce the uncertainty of voltage measurements. The other option is to purchase a manometer capable of measuring higher gauge pressures.

6 Summary

In this study a cost-effective set-up to calibrate rotameters and thermal mass flow meters in the air flow rate range (2…18) L/min is developed. In this calibration set-up, a diaphragm gas meter serves as a reference instrument to measure air flow rate. During the calibration process, two configurations of serial connections of the diaphragm gas meter and the gas flow meter are investigated, and the best set-up is chosen: the air flow is first passed through the gas flow meter and then through the diaphragm gas meter (figure 2). This set-up is chosen because it protects the diaphragm gas meter from damage caused by high gauge pressures in case the float of the rotameter blocks air flow. Compared with the traditional calibration methods, the designed calibration method is simpler and easier to operate and does not require large instruments such as bell prover.

The air tightness of the experimental set-up, which in most situations demonstrates a relative leakage less than 1%, is sufficient to calibrate gas flow meters at moderate flow rates. It potentially helps to calibrate gas flow meters at the Institute of Chemistry in future.

The study also focused on evaluating the measurement uncertainties of rotameter and thermal mass flow meter corrections at high and low air flow rates. The sources of measurement uncertainty mainly include instrument accuracies, random errors, reading errors, and systematic errors. Analyzing the main sources of uncertainty affecting the calibration of rotameters and thermal mass flow meters at high and low air flow rates, it is found that the permissible error of diaphragm gas meter and leakage of the set-up together contribute more than 60% to the expanded uncertainty. The effect of the tilted position of the rotameter and the resolution and repeatability of the rotameter and thermal mass flow meter readings contribute moderately to the corresponding expanded uncertainties. This analysis can be used to further improve the methodology in future.

The results also showed that at the flow rate of 12.61 L/min, the expanded uncertainty (*k*=2) of the rotameter correction was 0.30 L/min while at the air flow rate of 3.35 L/min the expanded uncertainty of the rotameter correction was 0.09 L/min.

For the thermal mass flow meter, the expanded uncertainty at the air flow rate of 17.95 NL/min (normal liters per minute) was 0.42 NL/min while the expanded uncertainty at the air flow rate of 2.02 NL/min was 0.05 NL/min.

Additionally, the effect of potential tilt on the rotameter readings was measured and for tilt 1° the average error in the readings was -0.61%.These results provide a reference for similar flowmeter calibration experiments in future.

Several recommendations are made to further improve the calibration system. These include regular calibration of diaphragm gas meter with low uncertainty, preparing vessels that can withstand higher pressures without leaks and also installing a mass flow controller in the flow path to improve the stability of rotameter readings.

7 Summary in Estonian

Rotameetrite ja soojuslike massivolumõõturite esialgse kalibreerismisstendi arendamine

Käesolevas töös konstrueeriti kulutõhus stend rotameetrite ja soojuslike massivoolu mõõturite kalibreerimiseks õhu mahtkiiruse vahemikus (2...18) L/min. Selles kalibreerimisstendis täidab membraangaasiarvesti tugimõõtevahendi rolli õhu mahtkiiruse mõõtmisel. Töös uuritakse kahte membraangaasiarvesti ja gaasivoolumõõturi vahelise jadaühenduse konfiguratsiooni ning valitakse parim konfiguratsioon: õhuvool juhitakse kõigepealt läbi kalibreeritava gaasivoolumõõturi ja seejärel läbi membraangaasiarvesti (joonis 2). Selline konfiguratsioon aitab kaitsta gaasiarvestit ülerõhu eest, kui rotameetri hõljuk blokeerib gaasi voolu. Võrreldes traditsiooniliste kalibreerimismeetoditega on arendatud kalibreerimismeetod lihtsam ja kergemini kasutatav ning ei nõua suuri instrumente, nagu näiteks gasomeeter.

Katsestendi üldine õhupidavus (suhteline leke enamasti alla 1 %) on piisav, et kalibreerida gaasivoolu mõõtureid mõõdukate vooluhulkade juures. Arendatud stend aitab tulevikus potentsiaalselt kaasa gaasivoolu mõõturite kalibreerimisele TÜ Keemia Instituudis.

Töös keskenduti ka rotameetri ja soojusliku massivoolumõõturi parandite mõõtemääramatuste hindamisele kõrge ja madala õhu mahtkiiruse juures. Mõõtemääramatuse allikad hõlmavad peamiselt mõõteriistade täpsust, juhuslikke vigu, lugemite võtmise vigu ja süstemaatilisi vigu. Analüüsides peamisi mõõtemääramatuse allikaid, mis mõjutavad rotameetrite ja soojuslike massivoolumõõturite kalibreerimist suure ja väikese õhu mahtkiiruse juures, leiti, et gaasiarvesti lubatud viga ja katsestendi lekked panustavad laiendmääramatusesse kokku rohkem kui 60%. Rotameetri kallutatud asendi mõju ning rotameetri ja soojusliku massivoolumõõturi näitude lahutusvõime ja korratavus panustavad mõõdukalt vastavatesse laiendmääramatustesse. See analüüs aitab kaasa metoodika edasisele täiustamisele tulevikus.

Tulemused näitasid, et õhu mahtkiiruse 12,61 L/min juures oli uuritud rotameetri parandi laiendmääramatus (k=2) 0,30 L/min, samas kui õhu mahtkiiruse 3,35 L/min juures oli rotameetri parandi laiendmääramatus 0,09 L/min. Soojusliku massivoolumõõturi laiendmääramatus õhuvoolu kiiruse 17,95 NL/min (normaalliitrit minutis) juures oli 0,42 NL/min, samas kui laiendmääramatus õhuvoolu kiiruse 2,02 NL/min juures oli 0,05 NL/min.

Lisaks mõõdeti töös ka potentsiaalse kalde mõju rotameetri näitudele ja 1° kalde korral oli keskmine viga -0,61%. See tulemus sobib tulevikus sarnaste rotameetrite kalibreerimiseks.

Kalibreerimisstendi edasiseks parandamiseks on esitatud mitu soovitust, milleks on membraangaasiarvesti regulaarne kalibreerimine väikese mõõtemääramatusega, õhupidavamate anumate valmistamine suuremate rõhkude jaoks ja massivooluregulaatori paigaldamine kalibreerimisstendi eesmärgiga parandada rotameetri näitude stabiilsust.

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Appendices

Appendix 1

Derivation of rotameter equation [5,7]:

When the float in a rotameter maintains a stable position, the relationship between the three forces acting on the float is:

$$F_g = F_b + F_d \quad \text{(i)}$$

where F_g represents the gravitational force, F_b represents the air buoyancy force, and F_d represents the air drag force.

Continuing the derivation of Equation (i):

$$F_g - F_b = F_d \quad \text{(ii)}$$

then,

$$F_g = mg = V_{float}\rho_{float}\, g \quad \text{(iii)}$$

$$F_b = V_{float}\rho_{gas} g \quad \text{(iv)}$$

$$F_d = \frac{C_d A_f \rho_{gas} v_{gas}^2}{2} \quad \text{(v)}$$

where,

m: the mass of the float in kg;

g: the gravitational acceleration in m/s²;

V_{float}: the volume of the float in m³;

ρ_{float}: the density of the float in kg/m³;

ρ_{gas}: the density of the fluid in kg/m³;

v_{gas}: the velocity of fluid in rotameter in m/s;

A_f: the cross-sectional area of the float in m².

Integrating equations (iii), (iv), and (v):

$$v_{gas} = \sqrt{\frac{2V_{float}\, g(\rho_{float} - \rho_{gas})}{C_d A_f \rho_{gas}}} \quad \text{(vi)}$$

The flow rate (Q) is expressed as:

$$Q = A_s v_{gas} \quad \text{(vii)}$$

where,
A_s: the cross-sectional area of the rotameter tube in m².

Introducing equation (vi) into equation (vii) it is possible obtain the volume flow rate of gas through a rotameter:

$$Q = A_s \sqrt{\frac{2V_{float}g(\rho_{float} - \rho_{gas})}{C_d A_f \rho_{gas}}} \quad \text{(viii)}$$

Appendix 2

The pictures of experimental set-ups:

Figure i. The first set-up

Figure ii. The second set-up

Figure iii. The air source in the experiments

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