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Implementation of the dynamic flying start-stop method in the pVTt gas flow standard

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Abstract

The gas flow standards using the volumetric method with a constant volume (pVTt) determine the flow rate based on the rate of mass change determined by measuring the density of the gas inside a constant volume. These standards normally use the static method of mass determination and rarely the dynamic one, due to dynamic changes of the gas temperature during mass collection. We have developed the analytical model that predicts the change of temperature in the pVTt system for gas flow rates up to 12 mg/min. Both measurement methods, the static and the dynamic, were implemented in the measuring system, with the dynamic method being corrected using the analytical model. The analytical correction model was validated by a comparison between the flow-rate measurements using the static and the dynamic methods. Based on successful validation of the analytical model we believe the corrected dynamic method is a viable alternative to the static one for the considered flow range.

1. Introduction

Constant volume volumetric standards, commonly abbreviated as pVTt (pressure, volume, temperature and time), are commonly used primary standards for measurements of gas flow rate [1-6]. They can be applied for different flow ranges; up to 77 m^3/min [2] and down to 2x10^{-5} ml/min [3], with the best standards reaching uncertainties as low as 0.013% [4]. At *Laboratory of Measurements in Process Engineering*, we have recently developed the pVTt standard designed for flow rates between 0.12 mg/min and 12 mg/min, with target uncertainty being 0.2% of the measured value. [6].

The pVTt standard determines the flow rate q_m of the gas through a change in its density $\Delta\rho$ within a constant measuring volume V_mea that occurred in a defined collection time t_col. They usually use the flying start stop method, which can be realized by using a diverter element to divert the gas flow from/to the measuring volume. Their basic measurement model reads as:

$$q_m = \frac{V_\mathrm{mea}}{t_\mathrm{col}}\Delta\rho \ . \qquad (1)$$

Depending on how the initial and final densities used to calculate the density change and the collection time are determined, we distinguish between the static and the dynamic methods.

In the static method, the start and end densities are captured before and after the collection of the mass when the mass of the gas in the measuring volume does not change in stable temperature and pressure conditions. The collection time is determined through the measurement of the time in which the flow rate was diverted into the measuring volume t_mea and the time correction t_cor that takes into account the diverter effects [6]. Thus, the basic measurement model for the static method can be written as:

$$q_\mathrm{m}^\mathrm{s} = \frac{V_\mathrm{cyl}+V_\mathrm{con}}{t_\mathrm{mea}+t_\mathrm{cor}}\left(\rho(p_\mathrm{end},T_\mathrm{end})-\rho(p_\mathrm{start},T_\mathrm{start})\right). \qquad (2)$$

The problem with the static method is the time measurement related to the diverter action and the resulting time correction. In contrast, the dynamic method is performed by determining the start and end densities (using the recorded temperature and pressures) during the gas mass collection in the measuring volume at two time instants (t_start and t_end). The time difference between t_start and t_end is considered as the collection time. The measurement model of the dynamic method is as follows:

$$q_\mathrm{m}^d = \frac{V_\mathrm{cyl}+V_\mathrm{con}}{t_\mathrm{end}-t_\mathrm{start}}\left(\rho(p_\mathrm{end},T_\mathrm{end})-\rho(p_\mathrm{start},T_\mathrm{start})\right). \qquad (3)$$

In practice, it turns out that determining the actual average density of the gas in the measuring volume is problematic due to dynamic changes of measured quantities, which means that the time response of the measuring equipment and also the measuring position of the measured quantities plays an important role.

Most pVTt systems use the static method, which was initially also used in our pVTt standard [6]. This article presents the implementation of the dynamic method, which required several adjustments to the measuring system. The most important was the introduction of the measured temperature correction using an analytical model that predicts the temperature change during the mass collection. In addition, we also had to implement real-time readings of digital data from the pressure transducer. The implementation of the dynamic method was validated comparing the flow rate measurement results obtained using the static and the dynamic method.

2. Analytic model

The presented analytic model describes the temperature field within the measuring volume filled with a constant flow rate. If this flow rate and the measuring volume are small, we can assume that only the processes of the heat transfer, the heat generation as a consequence of the density change, and the heat accumulation take place within the volume. The basic equilibrium equation for a stationary and homogeneous continuum is [7]:

$$\nabla^2 T(\mathbf{r},t)+\frac{1}{k}g(\mathbf{r},t)=\frac{1}{\alpha}\frac{\partial T(\mathbf{r},t)}{\partial t}\ , \tag{4}$$

where $T(\mathbf{r},t)$ is the temperature, $g(\mathbf{r},t)$ is generated heat rate at a point defined by the location vector $\mathbf{r}$ at time t, k is the thermal conductivity and α is the thermal diffusivity.

The most common form of measuring volume in pVTt flow standards is a cylinder, so the domain under consideration will be a right cylinder of length $2L$, radius b and volume V_{cyl}. We will be taking into account axial symmetry and symmetry transverse to the central axis. The cylinder is thermally stabilized so the whole domain has an initial condition equal to the initial temperature T_0, in addition, the walls have a large thermal capacitance, so there we will take into account the boundary condition of constant temperature T_0. The boundary conditions of symmetry and constant temperature are shown in Figure1.

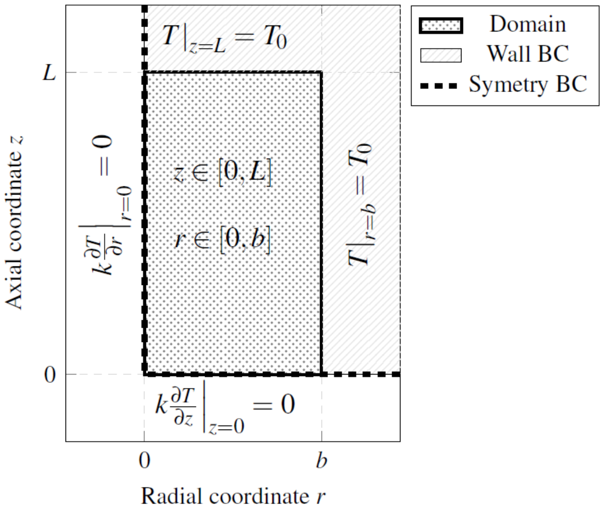

Figure 1: Definition of the domain and boundary conditions

Formulation of the heat generation resulting from the density change can be found in [8]. After simplification it is written as:

$$g(t)=T_0C_{\mathrm{V}}(\gamma-1)\frac{q_m^{cyl}}{V_{cyl}}\ , \tag{5}$$

where γ is the heat-capacity ratio, C_{v} is the volumetric specific heat capacity, the T_0 is initial temperature of the gas and $q_{\mathrm{m}}^{\mathrm{cil}}$ is the flow rate entering the.

The problem defined above is solved with the help of Green's functions [9]. From the solution the average temperature change $\tau=\bar{T}-T_0$ can be written as:

$$\tau(t)=\sum_{m,n=1}^{\infty}\frac{64Lq_{\mathrm{m}}^{\mathrm{cyl}}T_0C_{\mathrm{v}}(\gamma-1)\cos[n\pi]^2}{k(1-2n)^2\pi^3J_0[m]^2C'_{mn}} \times\left(1-\exp\left[\frac{-\alpha t}{4L^2b^2}C'_{mn}\right]\right), \tag{6}$$

with:

$$C'_{mn}=b^2(1-2n)^2\pi^2+4L^2J_0[m]^2 \tag{7}$$

and $J_0[m]$ as m^{th} zero of Bessel function of the first kind and 0th order.

3. Measuring system

Main parts of the pVTt standard (Figure 2) are a mass flow source (Bronkhorst, F-201CV-020), a pneumatically driven diverting valve (Swagelok, SS-41GXS 3MM-A15XD) with inductive sensor, a calibrated cylinder, two pressure transducers, one absolute (MENSOR CPG2500, range 300 kPa) and one differential (MENSOR CPT9000, range 2.5 kPa), a temperature probe with a temperature logger (TetraTec Instruments, WIT-S / Pico Technology, PT-104), DAQ card with counter (NI, USB-6341) and auxiliary components (valves, volumes, connecting tubes). The volume of the calibrated cylinder V_{cyl} (99.96 cm^3) was determined with dimensional measurements. To obtain the total measuring volume V_{mea}, we sum the V_{cyl} and the connecting volume V_{con} (2.89 cm^3), which was determined by means of the pressure expansion method [1]. The temperature T_{mea} is measured with the temperature probe inserted into a bore in the wall of the calibrated cylinder. For the purposes of thermal stabilization, most of the components are immersed in a water bath and the whole measuring system is placed in a climatic chamber. The entire measurement is controlled and recorded using a PC and the Labview programming environment. The control/measurement connections of the components are presented in Figure 3. To physically control the pVTt standard and to conduct the measurements the system uses a PLC and a set of solenoid valves driving pneumatic actuators of the valves. To calculate the flow rate, we also need the gas material properties, which are determined with the REFPROP database [10], using the measured pressure and temperature as the input parameters.

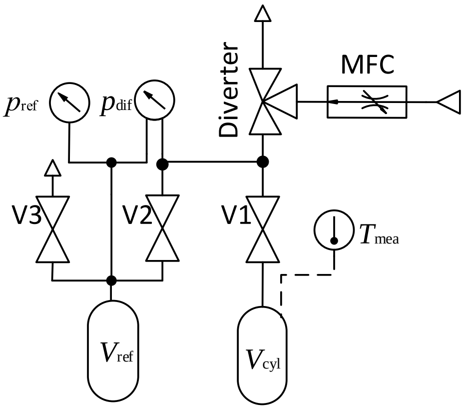

Figure 2: Basic schematics of the PVTt standard

The absolute pressure transducer measures the reference pressure p_{ref} in an additional reference volume V_{ref} that is closed during the measurement and immersed in the water bath to make it thermally stable. The differential transducer measures the pressure difference p_{dif} between the measuring and the reference volume. Hence, the absolute pressure in the measuring volume is determined as the sum of both pressure transducers outputs. The measurement starts with a zero pressure difference and it increases when the gas mass is collected. To add a time stamp on the measured differential pressure the transducer is connected to a microcontroller (Arduino Mega 2560, with additional 32-bit counter (Texas Instruments, SN74LV8154) and 32 kHz temperature-compensated crystal oscillator (Maxim Integrated, DS32kHz).

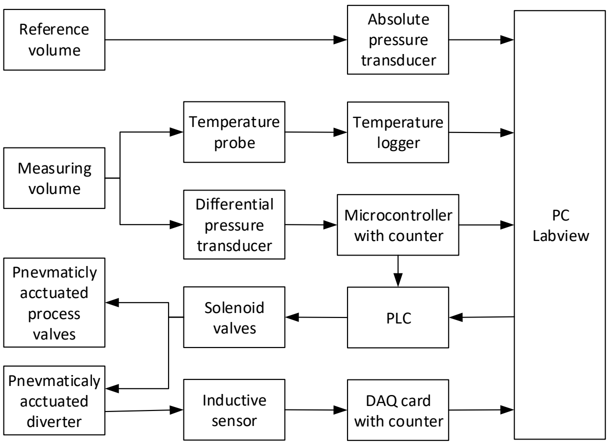

Figure 3: Control and measurement connections of the components

4. Implementation of the measurement method

The implementation of the dynamic and the static method for the presented measuring system was realised in LabVIEW environment. The control program is divided into three parts: the measurement loop that continuously monitors the reference pressure, the differential pressure and the temperature, the control sequence that implements the detailed measurement procedure, and the calculation block that determines the flow rate accounting for the temperature correction.

4.1 Measurement loop

The measurement loop is continuously pooling for the temperature, the reference pressure and the differential pressure. While for the first two the PC is connected directly to the transducer/logger, the last one is being read using additional microcontroller to achieve real time operation. The differential transducer is set into a mode where it outputs a digital value (serial communication) as soon as the A/D conversion finishes (approximately 57 values per second). When microcontroller detects the incoming message it signals the counter to store its current value into internal registers. When the whole message is received, it is processed and the pressure value is converted from the ASCI string into the float data type. As the counter is reset at the beginning of the measurement sequence, the time stamp (unsigned long data type) read from it represents a number of oscillations of the used crystal oscillator since the counter reset. As we are mainly interested of the difference between two values of pressure, the initial time does not have an effect. The last time stamp and the differential pressure in the microcontroller memory are then send on a request to the PC, which reads it as fast as it can. In order to save data needed for flow rate measurement, the sequence defines measurement intervals during which the average values of all tree monitored quantities and the recorded differential pressure within the interval are stored.

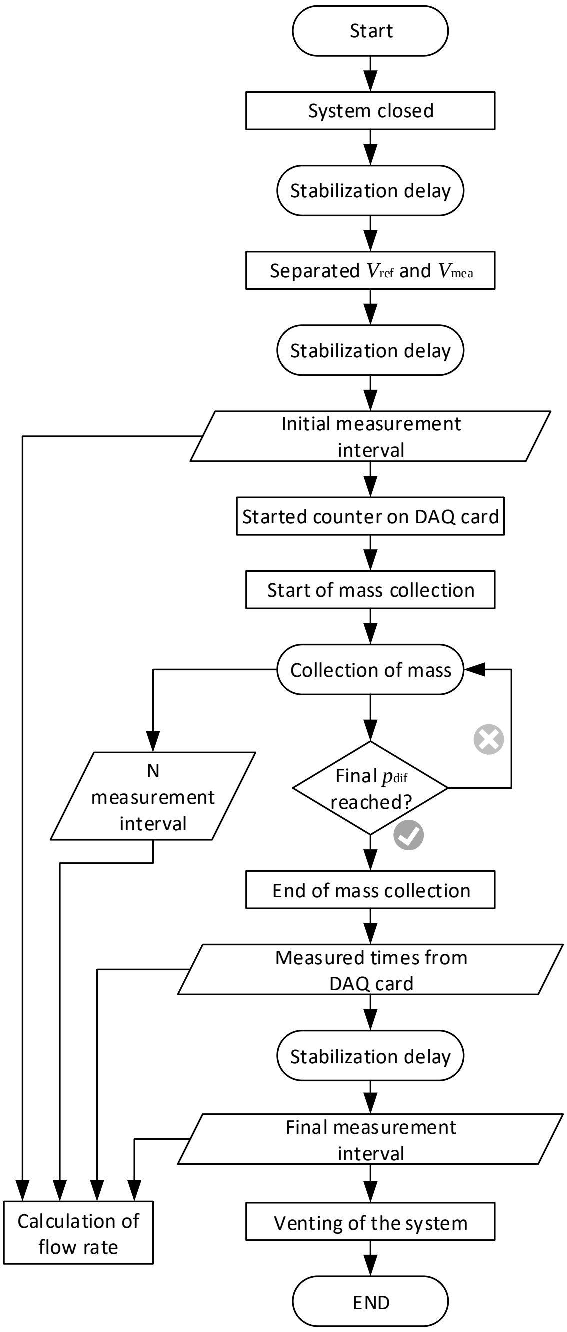

Figure 4. Flow chart of the measurement

4.2 Control sequence

The flow chart of the control sequence is presented in Figure 4. The sequence starts with the reference and the measurement volumes and the diverter opened to the atmosphere. First the volumes are separated (closed valve V3) from the atmosphere and then also separated from each other (closed valve V2). After adequate stabilisation the initial measurement interval is recorded. At the DAQ card a signal edge-separation time measurement is started, which is followed by the diverter action to start the mass collection. The collection is divided into the measurement intervals of predefined length (~10 s). When the final differential pressure is reached, the direct connection from microcontroller to the PLC is used to activate the diverter and stop the mass collection. The measured collection time is received from the DAQ card. After stabilisation the final measurement interval is recorded. The sequence is finished with venting of the volumes to the atmosphere by opening valves V2 and V3.

4.3 Calculation of the flow rate

The gas flow rate according to the static method is calculated using average values of the temperature and pressures in the initial and the final measurement interval. As the diverter is set to operate with the fastest achievable speed (approximately 0.07 s/divertion) in both directions, the collection time is obtained as the sum of the DAQ card measured time and the constant correction time. Detailed presentation of the procedure to determine the correction time was shown in [6].

To define the collection time in the dynamic method, two predefined differential pressure limits are used. The times t_{start} and t_{end} are defined by observing where the predefined limits of the recorded differential pressure signal are exceeded. To reduce noise, a local linear interpolation is used to obtain the average differential pressure at the respective time instants. Combined with the average temperature and the average reference pressure in the corresponding mesurement interval, the gas densities at t_{start} and t_{end} are determined and the flow rate for the uncorrected dynamic method is calculated using equation (3).

The so-called uncorrected flow rate is not accurate as the measured temperature does not correspond to the actual gas temperature during the mass collection. In order to calculate the temperature correction according to equation (6), we need to define additional parameters:

- the material properties of the gas are determined for the initial temperature T_0 and the initial pressure defined from the initial measurement interval,
- the actual dimensions of the measurement cylinder,
- the uncorrected flow rate is further reduced according to the ratio between the volume of the cylinder and the connecting volume to obtain the actual uncorrected flow rate entering the cylinder:

$$q_{\mathrm{m}}^{\mathrm{cyl}} = q_m^d \frac{V_{\mathrm{cyl}}}{V_{\mathrm{cyl}} + V_{\mathrm{con}}} , \tag{8}$$

- the time elapsed from the collection start is defined using the differential pressure time stamps. To define the instant of the collection start, the last value of the pressure when the mass collection has not yet taken place (limit change of 1 Pa) is looked for, and the value of its time stamp is set to zero with all others shifted accordingly.

After obtaining the temperature change from the correction model, the mass flow rate for the corrected dynamic method reads as:

$$q_{\mathrm{m,c}}^d = \frac{V_{\mathrm{cyl}} + V_{\mathrm{con}}}{t_{\mathrm{end}} - t_{\mathrm{start}}} \times \left(\rho(p_{\mathrm{end}}, T_{\mathrm{end}} + \tau_{\mathrm{end}}) - \rho(p_{\mathrm{start}}, T_{\mathrm{start}} + \tau_{\mathrm{start}}) \right). \tag{9}$$

5. Validation

The static and dynamic methods were implemented simultaneously for measurements of the gas flow rate, which made it possible to directly compare their results. For the dynamic method, we defined three combinations of the limiting pressure within which we calculated the flow rate (0.2-1.2 kPa, 0.2-2.4 kPa and 1.2-2.4 kPa). The comparison was carried out at two flow rates, at 3 mg/min and at 12 mg/min. It should be noted that the collection time decreases proportionally with increasing flow rate. The figures show the relative error between the mass flow rate resulting from the uncorrected as well as the corrected mass flow rates obtained with the dynamic method and the mass flow rate obtained with the static method.

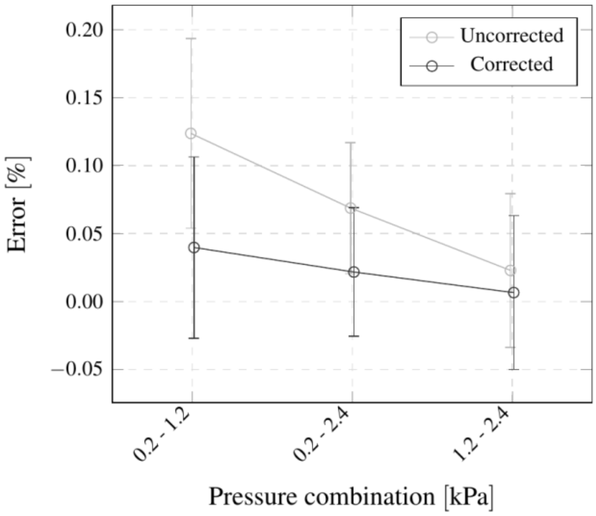

Figure 5: Relative errors of the corrected and uncorrected dynamic methods at the flow rate of 3 mg/min.

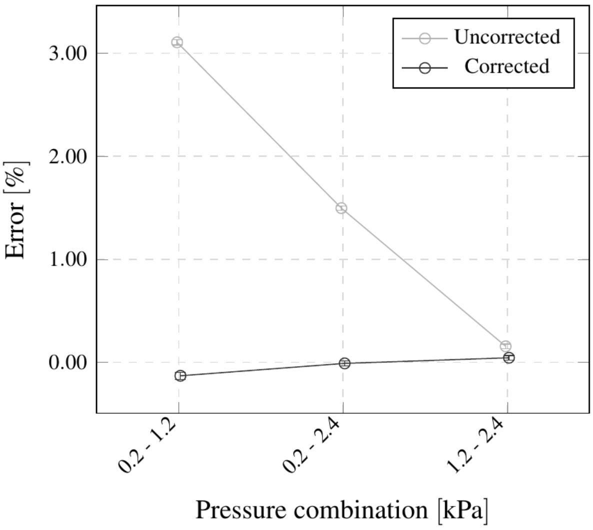

Figure 6: Relative errors of the corrected and uncorrected dynamic methods at the flow rate of 12 mg/min.

At the flow rate of 3 mg/min, the average error of the dynamic method is already below 0.2% for all observed pressure combinations. Considering the temperature correction (~0.05 K), the error decreases below 0.05 %. At the flow rate of 12 mg/min the average error of the uncorrected dynamic method rises to 3.1% for the first pressure combination, but falls to 0.16% for the third pressure combination. When the correction is introduced (~0.19 K), the average error in the first pressure combination is -0.13% which indicates that the correction was too large; i.e., the analytical model predicted too large temperature change. This may be due to an increase in the proportion of convective heat transfer in the initial measurement phase or to a dynamic error of the differential pressure transducer. The average error in the other two pressure combinations falls below 0.05% after correction.

We conclude that, taking into account the correct combination of the pressures and avoiding the starting interval of the mass collection with the greatest dynamic changes, the dynamic method considering the temperature correction can archive comparable results to the static method.

6. Conclusion

We have successfully implemented the dynamic method of mass determination into our pVTt standard. Its implementation was validated by comparison of the measured gas mass flow rates with the one resulting from the static method. By considering the presented temperature correction model, the errors between the mass flow rates obtained with the dynamic and static methods are smaller than the target uncertainty.

Following successful implementation, a comprehensive uncertainty analysis of the corrected dynamic method will be conducted. We will have to focus on uncertainties related to timing and dynamic errors of the pressure transducer and on uncertainty of the implemented correction. To verify both a reliable computational fluid dynamics simulation will be set up and compared with the measured pressure and predicted correction of the temperature.

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