Flomeko 2000 - IMEKO TC9 Conference
Salvador, Bahia, BRAZIL
4-8 June, 2000

A Silicon Flow Sensor for Highly Accurate Mass Flow Measurement

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April 15, 2000

Abstract

We describe a thermal, silicon integrated, mass flow sensor for highly accurate mass flow measurements over a large dynamic range. Offset-drift is completely eliminated by application of the VanPutten-ADM method. The method is illustrated using air. The total measurement uncertainty is typically $< 1\%$ of reading, with a turndown larger than 1:1000.
keywords: thermal, silicon flow sensor, VanPutten-ADM

1 Introduction

Gas flow measurement is a widespread activity in our society, were applications range from fiscal measurements (*e.g.* domestic gas consumption), process control, meteorology and research. Many measurement principles exist, varying from mechanical (rotating vanes, moving pistons) to differential pressure, coriolis or thermal. In practice, the measurement principle applied is typically dictated by the specific application. Thermal flow measurement, for instance, is well-suited for measurement of variables occurring in turbulent flows, such as mean- and fluctuating velocity components; other applications are measurement of low Re number flow, where differential pressure measurement is not sensitive enough to detect pressure changes.

All thermal flow sensors measure changes in the heat transfer, whether local (temperature gradients) or global (changes in total power dissipation), as a function of the Re number, Re=$\rho v L/\eta$, with ρ the density, v the velocity, η the dynamic visocisity and L a characteristic length. Therefore, thermal flow sensors are considered *mass flow sensors*, since the mass flux, ϕ_m (kg/s m^2), is contained in the Re number as Re=$\phi_m L/\eta$. The most well-known method of thermal flow measurement is probably the hot-wire anemometry. Drawbacks of this technique have always existed, however, such as the need for regular re-calibration. This has motivated research into different (thermal) sensing devices, for instance thermal silicon flow sensors.

2 Thermal silicon flow sensors

In 1974 the first thermal flow sensor in silicon was realized by a development of van Putten and Middelhoek at Delft University of Technology [1], and improvements based on this first design [2, 3], as well as variations [4], quickly followed. This research was motivated by the possible strong advantages of silicon technology for sensor design, for example inexpensive mass production, small size, robustness and reliability. It took many years, however, to develop sensors that were suitable for real-world applications, such as measurement of outdoor air flow [5], vacuum cleaners [6], microphones [7] and respiratory flow [8].

Here, we will discuss a silicon *vector* sensor, that allows measurement of flow velocity and direction across its surface, in the application of mass flow measurement. The design of the sensor is based on the original configuration proposed by van Putten sr. in 1980 and 1985 [3, 9].

3 Working principle

The sensor consists of a silicon chip, that is operated at at *constant mean surface temperature*, T_w, typically between 70 and 120°C. A flow applied across the sensor surface induces a small temperature gradient, $\partial T_{xy} \ll T_\mathrm{w}$, as illustrated in figure 1.

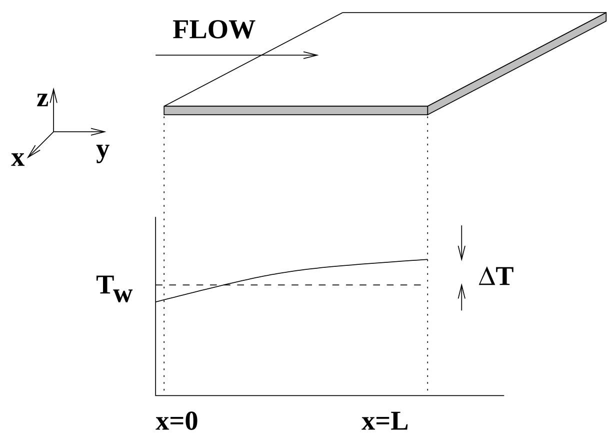

Fig. 1. Basic principle of the gradient measurement. The size of the sensor is 4×4 mm. Below the temperature gradient over the sensor surface is indicated. The temperature gradient is very small, typically a few milli K.

This stream-wise gradient is detected by an integrated measurement bridge, and contains the flow signal, V_grad. Assuming an ideal sensor, we can write

$$V_\mathrm{grad} = g(\mathrm{Nu}, \Delta T) \tag{1}$$

with Nu the Nusselt number, that generally can be written as $\mathrm{Nu} = c_0 + c_1 \mathrm{Re}^n$. Therefore, this gradient measurement is directly related, through the Nu number, to the mass flow.

Although in theory eqn. 1 holds, in practice offset signals may be present that also contribute to the output signal. In our real world environment, therefore, eqn. 1 becomes

$$V_\mathrm{out} = g(\mathrm{Nu}, \Delta T) + E(U_1, U_2, \cdots, U_n) \tag{2}$$

where the function E is the contribution of all additive disturbing influences, or *offset*, on the sensor output signal. If the offset is a well defined constant, sensors may be designed with the possibility of offset compensation at the production site, for instance by suitable calibration. However, offset generally may vary (also known as *drift*) due to temperature variations, time, strain and stresses introduced by packaging, aging, etcetera. This creates a need for offset-reduction or drift-elimination methods that can be applied during each measurement. Especially at measurement of low air flow velocities, this influence may become relatively large. Furthermore, for long-term volume measurements, the function E may introduce unacceptable errors, *e.g.* in fiscal measurement applications. In order to essentially eliminate this error function E, the VanPutten-Alternating Direction Method [10, 11] was applied. This procedure uses the bidirectional sensitivity of the current sensor, which can be realized with suitable electronics. This implies that the function g in eqn. 2 has either a positive or negative sign, depending on the direction of the flow applied to the *vector* sensor (anisotropic dependency). The error function E, however, is generally *not* dependent on the flow-sensor orientation (isotropic dependency). In practice, therefore, a measurement is performed with two different flow-sensor orientations, were in measurement A we have

$$V_{\text{out}}^{A} = g(\text{Nu}, \Delta T) + E(U_1, U_2, \cdots, U_n) \tag{3}$$

and in measurement B

$$V_{\text{out}}^{B} = -g(\text{Nu}, \Delta T) + E(U_1, U_2, \cdots, U_n) \tag{4}$$

where subtraction yields the ADM-signal

$$V_{\text{ADM}} = 2g(\text{Nu}, \Delta T) + \epsilon. \tag{5}$$

The additive drift influence has now been reduced to $\epsilon = \partial E/\partial t$ over the time interval between the two measurements A and B, with $\epsilon \ll E$.

4 Methods

The sensor is positioned in the center of a tube with internal diameter D=32 mm, and area A_t, as illustrated in figure 2.

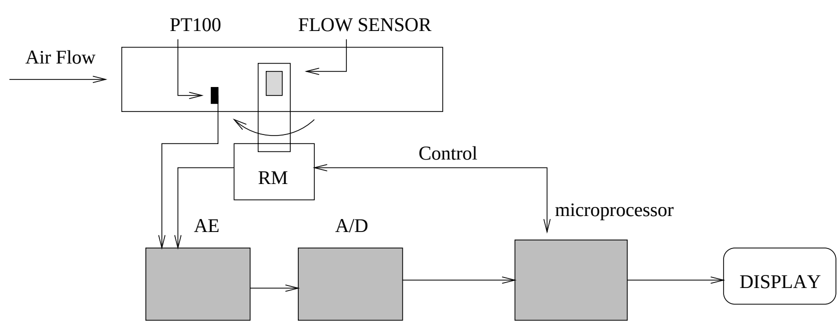

Fig. 2. Schematic illustration of the measurement setup. RM denotes the rotating mechanism. AE the analog electronics; A/D the analog to digital convertor (14 bit). The temperature sensor is a PT100 element.

A rotary mechanism (RM) realizes the change in flow-sensor orientation. Flow measurement is realized by a two-step procedure. Firstly, in position A of the sensor, the sensor output is measured by sampling at 20 Hz during 8 seconds. Subsequently, the sensor is turned around its axis, and again the output signal is sampled for another 8 seconds. Subtraction of the mean of these two signals yields the drift free signal, $V_{\rm ADM}$.

Due to its positioning and size, the sensor measures the *local* flow field around the sensor surface. Since, however, there is a fixed relationship between the local behaviour of the flow and the mean mass flow, $\phi_m A_t$, calibration allows (mean) mass flow measurement over the tube area. In figure 3, we show a schematic illustration of the measurement setup. Calibration is realized using an automated calibration setup, where different mass flows are applied, measured by a reference meter (total uncertainty ¡ 0.1% of reading), and fitting a polynomial function using eqn. 5. A semi-empirical relation between the Re number and the drift-free sensor signal, $V_{\rm ADM}$, is given by

$$\mathrm{Re} = \sum_{n=1}^{N} \left[V_{\rm ADM}^{a} (\Delta T)^{b} \right]^{n} \tag{6}$$

where ΔT is the sensor-gas temperature difference; a and b are constants. The value of N is typically between 2 and 5.

5 Results

In figure 3 the principle of the VanPutten-ADM method is graphically illustrated.

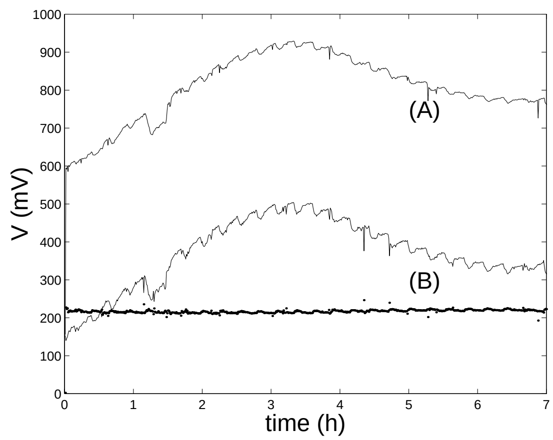

Fig. 3. Illustration of the bidirectional sensitivity of the flow sensor and the VanPutten-ADM-principle. Applied flow $\approx$ 1 SLM/min = constant. The upper curve labelled A represents the sensor output signal in the sensor-flow orientation of 0^0, the middle curve labelled B represents the output signal of the sensor in the 180^0 orientation. Drift is apparent from the deviation of the horizontal. The lower curve is the ADM-signal. This signal shows practically no drift. The measurement time was 7 hours.

This measurement was carried out during constant flow conditions. The curve labelled A represents the sensor signal at orientation 0^0. Drift is apparent from the deviation from the horizontal. The *exact* same behaviour, except for a baseline shift, is shown by the bottom curve, B, as measured by changing the relative orientation of the sensor and the medium (the flow), corresponding to 180^0 orientation. By subtracting these two signals on consecutive time intervals, one obtains the ADM-flow signal, $V_{\rm flow}^{\rm ADM}$, as shown in the same figure (lower curve). A typical response curve is shown in figure 4, compensated for changes in the gas temperature between 16 to 25 °C.

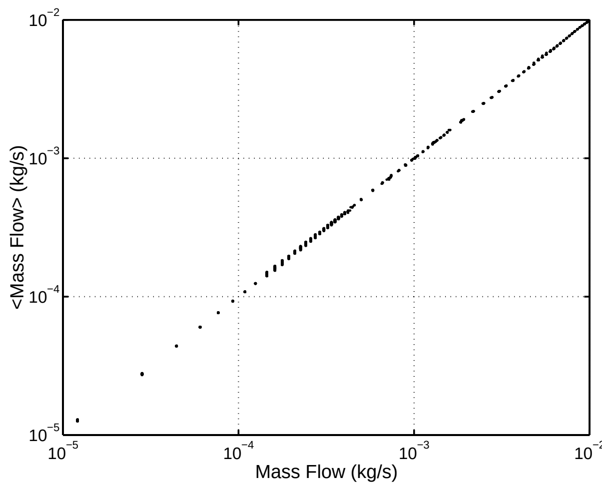

Fig. 4. Calibration curve in the temperature range 18-25 °C. The total measurement uncertainty is typically less than 1% over the range $0.02 \cdot 10^{-3}$ to $10 \cdot 10^{-3}$ kg/s, increasing to a few percent below $0.02 \cdot 10^{-3}$ kg/s. Note that the we used a log-log scale.

For the fitting routine, eqn. 6 was applied, with n=5. The measurement range obtained is from 0.01 $\cdot 10^{-3}$ to $10 \cdot 10^{-3}$ kg/s (0.5 to 500 SLM). In the range $0.02 \cdot 10^{-3}$ to $10 \cdot 10^{-3}$ kg/s, the total measurement uncertainty is typically less than 1%, increasing to a few percent below $0.02 \cdot 10^{-3}$ kg/s.

6 Discussion and Conclusion

We present a method for mass flow measurement based on silicon flow sensor technology. The (vector) sensor applied detects a flow induced temperature gradient across its surface, that serves as a measure for the mass flow. This allows application of the VanPutten-ADM method to effectively eliminate offset-drift. We were able to realize mass flow measurement over a large dynamic range, from $0.01 \cdot 10^{-3}$ to $10 \cdot 10^{-3}$ kg/s (0.5 to 500 SLM) with a total measurement uncertainty typically less than 1% of the reading, except for flows smaller than about $0.02 \cdot 10^{-3}$ kg/s, where the uncertainty was slightly larger. This flow region, however, was below the calibrated measurement range of the reference meter used, which will contribute to the total measurement uncertainty.

For completeness, we remark that another interesting feature of the gradient measurement is the ability to measure extremely low flow velocities (downto 1 mm/s), which is far into the mixed flow region [12]. In this flow region, measuring changes in power dissipation to estimate the flow velocity generally fails, due to the disturbing influence of the natural convection, caused by heating of the air by the thermal flow sensor. This results in a strong flattening of the power response curve, or even the presence of (local) minima, making non-ambiguent readings impossible. This same phenomenon is responsible for the lower-limit of air flow measurements using hot-wires [13, 14]. In the current housing, the sensor is placed directly into the flow, making it potentially sensitive for contamination. Using clean air, however, has shown no significant effect on its performance thus far. Furthermore, an important advantage of this placement is the absence of a significant pressure drop. As for any thermal mass flow meter, measuring different gases necessitates different calibration curves, due to the dependence of the output signal on the thermal conductivity and the viscosity. Recently, a commercial mass flow meter based on this silicon technology, the VP4, was introduced by VPInstruments in Delft [15], as illustrated in figure 5.

Fig. 5. The commercial mass flow meter as recently introduced by VPInstruments in Delft. At the left, the controller is shown; at the right, the high-pressure housing in which the silicon sensor is positioned (not visible on the photograph).

A few of the unique features of this instrument are the absence of zero-drift and its large dynamic range (turndown 1:1000). The instrument is suitable for long-term, accurate gas volume measurements with nearly uniform uncertainties, typically less than 1% of reading. Other applications include mass flow measurements at pilot plants or verification of mass flow controllers.

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