Novel method for the realization of small differential pressures between 1 Pa and 1 kPa

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Abstract. This paper reports a novel method for the realization of small differential pressures in the range of 1 Pa and 1 kPa by using a precision wind tunnel with Laser Doppler Anemometer (LDA) and a Prandtl tube. The LDA system measures the wind speed of the precisely controlled wind tunnel and provides traceability to SI. A Prandtl tube immersed into the wind tunnel, relates the well-controlled airflow speed to the pressure difference of total pressure and static pressure at the point of measurement. Experiments have been performed in the range between 0.5 and 60 m/s air velocity corresponding to about 150 mPa and 2.2 kPa. The measurement uncertainty of the generated differential pressures between 1 Pa and 1 kPa are calculated to be around 0.8% (k = 2).

1 Introduction

The realization and measurement of low differential, positive and negative gauge pressures play an increasingly important role in various industrial areas such as power plants, cleanroom technologies, and petrochemical and pharmaceutical industry demanding very accurate pressure measurements at various stages of the metrological traceability chain. In hospitals, research laboratories and storages of toxic wastes low pressures are required to prevent the spread of germs and containments. Fabrication facilities for semiconductor technology and pharmaceutical product are relying on the control of small differential pressures above the ambient pressure for contamination protection.

Figure 1 shows conventional calibration procedures using a) liquid column manometers and b) dead-weight pressure balances and allow a realization of the pressure unit above 1 kPa and 5 kPa, respectively [1]. In case of pressure balances, the limiting factor is the mass of its pistons. To address the global mercury pollution, the EU restricts the use of mercury in barometers and manometers. Their replacement by oil manometers bears the drawback of the relatively large variation and instability of the oil density.

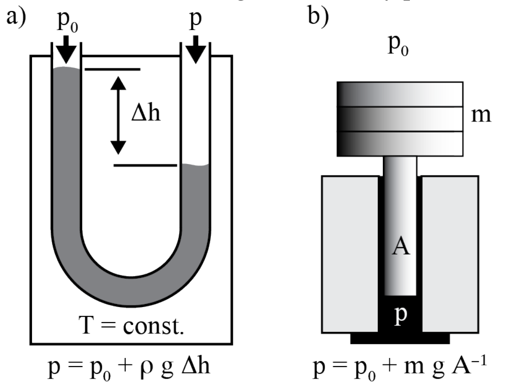

Fig. 1. Realization of the pressure scale by a) liquid column manometers and b) dead-weight pressure balances.

New force-balanced piston gauges (FPGs) allow an accurate measurement of pressures from 15 kPa downwards to zero with an accuracy level down to $6{\times}10^5 p_e + 5$ mPa [2,3], where p_e determines the external pressure. FPGs have been used so far as secondary standards only. They are calibrated against pressure balances or mercury manometers at pressures above kilopascals. Below 1 kPa FPGs represent currently no alternative for the dissemination of the pressure scale. In scope of the EURAMET project pres2vac, they are characterized in order to establish a primary standard.

A standard offering appropriate calibration methods for accurate state-of-the-art pressure sensors in the range of 1 Pa to 1 kPa is required to meet the industrial needs. This work presents a smart and novel method for the realization of small differential pressures by using a precision wind tunnel with Laser Doppler Anemometer (LDA) and a pitot tube.

2 Measurement Facilities

The wind tunnel system (WK8332060, Westenberg Engineering) of Testo Industrial Services GmbH is shown in Fig. 2 a). The system is of Göttinger Design and offers an open jet test section and closed return. The flow velocity is infinitely variable between 0.1 m/s to 68 m/s. The nozzle outlet diameter (shown in Fig. 3 b)) is 320 mm with a contraction ratio of 8. The measuring section is 470 mm long and the degree of turbulence is around 0.3% (at 20 m/s). The dimensions of the systems are 1530 mm (h) × 2800 mm (w) × 7040 mm (l).

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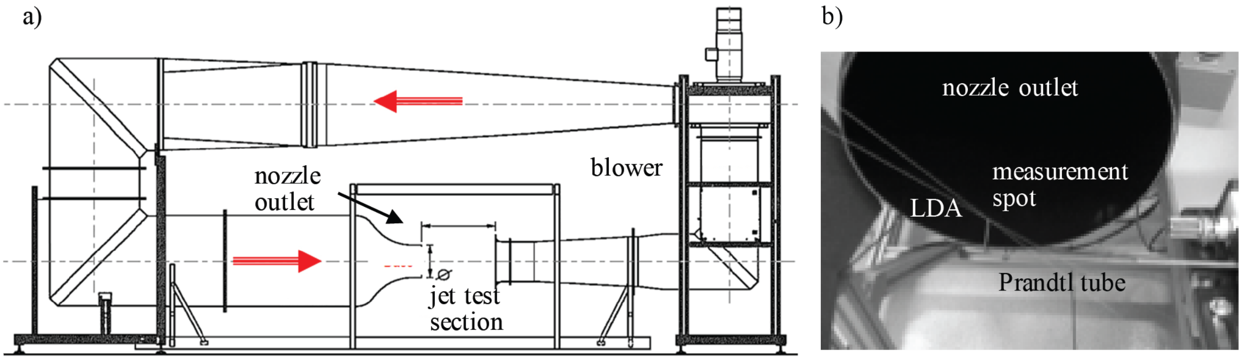

Fig. 2. a) Schematic of the wind tunnel system and b) close up picture of the jet test section with a Prandtl tube in the center of the measuring spot of the LDA.

To determine the airflow speed non-invasively and to provide metrological traceability to SI, an LDA system from ILA (Intelligent Laser Applications GmbH) is used. It is operated in the range from 0.1 to 68 m/s and has been calibrated by PTB with regard to its interference fringe distance with a measurement uncertainty ($k = 2$) of approx. 0.13%. The airflow speed is measured by the LDA system by detecting the moving speed of smoke particles carried by the airflow. For each velocity step 1000 bursts (or 20 seconds) are recorded.

To translate the air velocity to a differential pressure, a Prandtl tube is positioned in the center of the free jet at a distance of 100 mm from the nozzle, as shown in Fig. 2 b). The correlation between air velocity and differential pressure is derived by Bernoulli's principle. Figure 3 describes the operating principle schematically. In a stationary flow, the sum of static (p_s) and dynamic pressure (second term in (1)) is constant and equal to the total pressure p_t by

$$p_s + ½\, \rho\, v^2 = p_t \qquad (1)$$

Equation (1) relates the speed of the fluid v at a point to both the mass density ρ of the fluid and the pressures at the same point in the flow field. The density of air is calculated by the barometric pressure, temperature and humidity of the air stream close to the point of measure [4]. The dynamic pressure p_e at the output is calculated as

$$p_e = ½\, (v/S)^2\, \rho\cdot, \qquad (2)$$

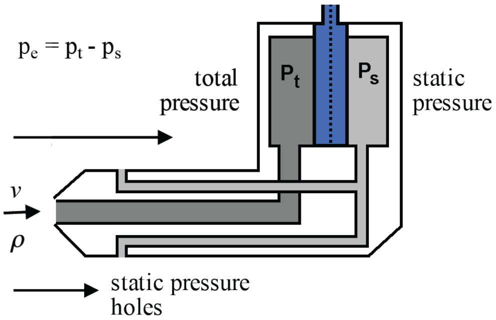

Fig. 3. Generation of a low differential pressure p_e at the output ports of a Prandtl tube.

where S is a dimensionless constant of the Prandtl tube close to $S = 1.00$ depending mainly on the construction of the tube. The exact factor of the tube needs to be determined. The utilized Prandtl tube (Airflow Developments) has an uncertainty of the constant S of about 0,35% ($k = 2$).

3 Results

3.1 Uncertainty of the wind profile

The generated air velocity can be expressed by the measured value of the LDA v_{LDA} and correction terms as

$$v = v_{\mathrm{LDA}} + \delta v_{\mathrm{WK,Stab}} + \delta v_{\mathrm{WK,Hom}} + \delta v_{\mathrm{WK,Turb}} \qquad (3)$$

where $\delta v_{\mathrm{WK,Stab}}$, $\delta v_{\mathrm{WK,Hom}}$ and $\delta v_{\mathrm{WK,Turb}}$ denote the the correction for the stability, homogeneity and turbulence intensity of the wind profile. The corresponding combined uncertainty of the generated air velocity is given by

$$u(v) = (u_{\mathrm{LDA}}(v)^2 + u_{\mathrm{WK,Hom}}(v)^2 + u_{\mathrm{WK,Stab}}(v)^2 + u_{\mathrm{WK,Turb}}(v)^2)^{1/2} \qquad (4)$$

Measurements of wind profiles were made from 0.5 to 60 m/s at nine different positions around the center of the nozzle in horizontal and vertical directions. Further, the temporal stability at each point has been investigated. The relative standard uncertainties $u_i(v)$ for the investigates air flow range are shown in Fig. 4. For low air velocities, the uncertainty is mainly determined by the homogeneity and stability of the wind tunnel. With increasing air velocities v, their impacts are decreasing. At 60 m/s the calibration uncertainty of the LDA and turbulence intensity has the main impact on the overall uncertainty $u(v)$. The expanded uncertainty ($k = 2$) at 10 m/s is extracted to be 0.18%.

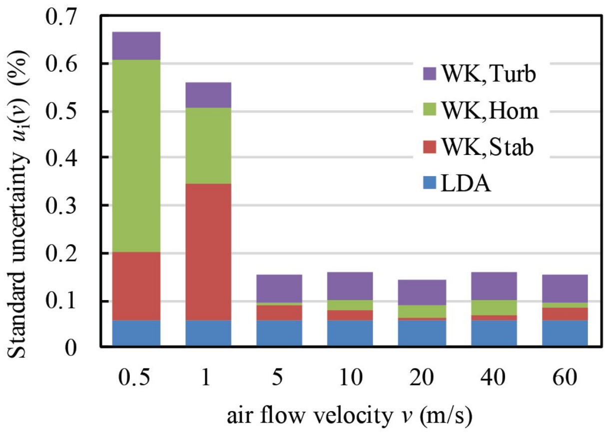

Fig. 4. Relative standard uncertainty components for the generated air velocity v.

3.2 Uncertainty of the generated differential pressure

Using Eq. (2) the combined uncertainty of the generated pressure p_e is obtained by

$$u(p_e) = (u_v(p_e)^2 + u_S(p_e)^2 + u_\rho(p_e))^{1/2} \quad (5)$$

with uncertainty contributions arising from the air velocity, Prandtl tube constant and air density. The contribution by the air density is calculated following the CIPM-2007 calculation [4]. The overall uncertainty budget for an airflow velocity of $v = 5.02$ m/s corresponding to a differential pressure of $p_e = 14.83$ Pa is shown in Table 1. The uncertainty of the constant of the Prandtl tube $u_S(p_e)$ has the strongest impact on the overall uncertainty with about 75%. The expanded uncertainty ($k = 2$) is calculated to be 0.12 Pa, which is equal to 0.81%.

Figure 5 presents the uncertainty components $u_i(p_e)$. Below 1 Pa the overall uncertainty is mainly determined by the contribution with respect to the air velocity in the wind tunnel. The expanded uncertainty ($k = 2$) reaches values of about 2%. Above 1 Pa the overall uncertainty is dominated by the contribution of the Prandtl tube.

Table 2. Uncertainty budget of the generated pressure at an airflow velocity of $v = 5.02$ m/s.

source	estimate	value (k=1)		distri-bution	sens. coeff.	std. uncert.	
X_i	x_i	a_i	unit	$P(x_i)$	c_i	$u_i(y)$ (Pa)	
p_e	14,83	0	Pa				
v	5,02	4,5E-03	m/s	N	$2\ p_e/v$	2,64E-02	19%
S	1,002	1,8E-03	-	N	$-2\ p_e/S$	-5,19E-02	75%
ρ	1,18	1,1E-03	kg/m³	N	$1\ p_e/\rho$	1,42E-02	6%
***U* mit k=2**						**1,20E-01**	

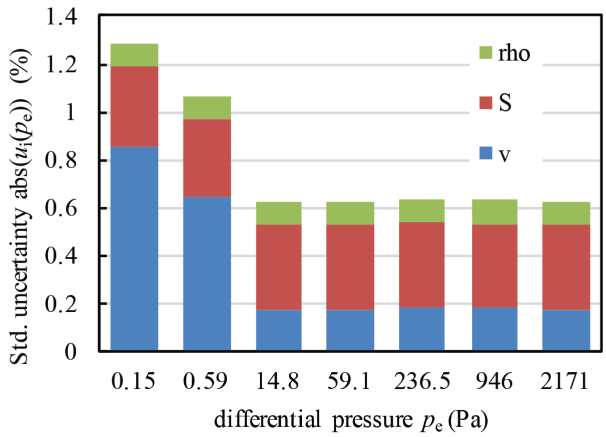

Fig. 5. Relative standard uncertainty components for the generated differential pressure p_e.

4 Discussion and Outlook

Small differential pressures in the range of 1 Pa to 1 kPa can be accurately generated using a wind tunnel with LDA and a Prandtl tube. The expanded uncertainty is in the range of 0.8% of p_e. The most pronounced contribution is due to the uncertainty of the Prandtl tube. Taking into account the CMCs of the PTB for static tubes (0.25%), an expanded uncertainty of about 0.6% would be feasible. In this case, the Prandtl tube would still contribute by more than 60% to the expanded uncertainty.

The overall limit of the expanded uncertainty is estimated to be around 0.5%. Smaller uncertainties will require smaller CMCs for static tubes and a better accuracy of the fringe fields calibration of the LDA. The latter seems feasible, however regarding static tubes, the NMIs have to better control the influence of the air density. Further work should also focus on the applicability of Bernoulli's law at low air speeds.

References

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