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A mixing method for traceable air velocity measurements

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Abstract

A novel and quite simple method to establish a traceability link between air velocity and the national standards of mass and time is presented in this paper. The method is based on the humidification of flowing air before the blower of a wind tunnel with a known mass flow of water. Then air velocity can be calculated as a function of humidification water flow. The method is compared against a Pitot-tube-based velocity measurement in a wind tunnel at the MIKES. The results of these two different methods agreed well, with a maximum difference of 0.7%.

Keywords: air velocity, wind tunnel, traceability, mass flow

1. Introduction

A wind tunnel is piece of research equipment that is traditionally used to study the effects of moving air around or over objects. It is also used for metrological purposes to generate a stable and accurate air flow velocity field in a test section. Metrological wind tunnels are usually low speed tunnels and they are based on an open or closed circuit of flowing air. The velocity of moving air is usually from 15 cm s^{-1} to 50 m s^{-1} [1]. The main components of the metrological wind tunnel are a settling chamber, contraction and a test section with an air velocity measurement system. An exit diffuser can be placed downstream of the test section. An air blower or fan is installed upstream of a settling chamber or downstream, after the test section or exit diffuser (if used).

Previously, Pitot-tubes were used as air velocity references in wind tunnels. Nowadays Pitot-tubes have been superseded by laser Doppler anemometers (LDAs) as primary standard instruments in metrological applications. The main reason for this is the better accuracy achieved with LDAs and the limitations of Pitot-tubes used in low air velocity measurements. The lower velocity limit for a Pitot-tube is around 2 m s^{-1} because of the limited accuracy in measuring so small a pressure difference between the dynamic and static pressures.

Traceable air velocity measurements are vital in all applications, where the absolute air speed value has to be known. Also, in relative measurements significant benefits can be obtained from demonstrated traceability. The traceability

is established through an unbroken calibration chain, i.e. a complete series of comparisons with stated uncertainties from the measurement set-up to national or international standards [2]. In air velocity measurements, it is most common to build the traceability link to the national standards for length and time by calibrating an LDA against a particle with a known speed. This can be realized, for example, by using a light scattering particle on the rim of a disk, which is rotating at a known velocity. From this the linear speed of the particle and a calibration factor of the LDA can be calculated [3, 4].

If a Pitot-tube is used as a reference instrument, the traceability is usually obtained by calibrating the Pitot-tube against an LDA which is traceable to length and time standards. At air velocities below the lower limit of a Pitot-tube, other methods are needed if an LDA is not possible to use. For example, calibration devices and methods based on mechanical systems [5, 6], the laminar flow in a pipe [7, 8] or piston-cylinder assembly [9] have been built for the purpose. In mechanical systems the anemometer to be calibrated is conveyed on a linear or circular track at a desired constant speed.

Instead of establishing different primary standards for different flow quantities, gravimetric mass flow standards are used as the primary source of traceability in the whole gas metrology field at the Centre for Metrology and Accreditation (MIKES). A novel method was developed to create a traceability link to air velocity measurements. The method is based on detecting the change in water vapour concentration due to controlled humidification in a wind tunnel. In this paper,

the method is called the mixing method (MM). When applying the MM, moist air flow measurements in the wind tunnel are traceable to the primary gravimetric gas flow standard and thus to the national standards of mass and time. The air density in the wind tunnel and the cross-section area of the wind tunnel nozzle are needed for converting the initially obtained mass flow rate to air velocity.

To demonstrate and validate the method, a small wind tunnel was constructed at MIKES. The tunnel is described in this paper. It is operating in the velocity range from 5 m s⁻¹ to 30 m s⁻¹. The MM was compared against a Pitot-tube based velocity measurement in the tunnel.

2. Mixing method for linking air velocity to mass and time standards

2.1. Overview

When humidifying air in a wind tunnel at a constant rate, the humidity of air in the test section is directly proportional to the air velocity. If the mass flow of evaporated water and the humidity difference between the inlet and test section of the tunnel are determined the air velocity in the test section can be calculated.

In the MIKES system, the evaporation mass flow is determined by means of dynamic weighing, i.e. by measuring continuously the mass of water fed into an evaporator. A dew-point hygrometer is used for measuring the humidity difference.

2.2. Theory

When air flows into a wind tunnel, the mixing ratio of the air is

$$r_{w1} = \frac{\dot{m}_{v1}}{\dot{m}_{a1}} \quad (1)$$

where \dot{m} is the time derivative of the mass, i.e., mass flow. The subscripts 'v' and 'a' refer to water vapour and dry air, respectively. After the humidification, the mixing ratio is

$$r_{w3} = \frac{\dot{m}_{v1} + \dot{m}_{v2}}{\dot{m}_{a1}}, \quad (2)$$

where \dot{m}_{v2} denotes the mass flow of humidification water. The mass flow of moist air at the inlet of the wind tunnel \dot{m}_1 can be written with the help of the mixing ratio and the mass flow of dry air:

$$\dot{m}_1 = (1 + r_{w1})\dot{m}_{a1}. \quad (3)$$

Taking into account equation (1), equation (2) can be written as

$$r_{w3} = \frac{r_{w1}\dot{m}_{a1} + \dot{m}_{v2}}{\dot{m}_{a1}}. \quad (4)$$

Solving \dot{m}_{a1} from equation (4) one obtains

$$\dot{m}_{a1} = \frac{\dot{m}_{v2}}{r_{w3} - r_{w1}}. \quad (5)$$

By substituting equation (5) in equation (3), the total mass flow rate in the test section of the wind tunnel can be stated as

$$\dot{m}_3 = \frac{(r_{w1} + 1)\dot{m}_{v2}}{r_{w3} - r_{w1}} + \dot{m}_{v2}. \quad (6)$$

The mass flow rate at the observation point is now a function of the mass flow of saturated water vapour and the mixing ratios of air in the inlet of the wind tunnel and at the point of interest. If the area of the channel is known, the gas velocity can be written as

$$v_3 = \frac{\dot{m}_{v2}}{\rho_{a3}A_3} \left[\frac{r_{w1} + 1}{\Delta r_w} + 1 \right], \quad (7)$$

where ρ_{a3} , A_3 and Δr_w correspond to the density of air, the cross-section area of the test point and the mixing ratio difference of air before and after the humidification, i.e., $\Delta r_w = r_{w3} - r_{w1}$, respectively. The density of air is calculated with the equations in [10].

2.3. Uncertainty analysis

In equation (7) the mixing ratio is measured indirectly with a dew-point hygrometer. The water vapour pressure p_v is calculated from the dew-point temperature (T_d) using Sonntag's formula:

$$p_v = S_0 \exp[S_1/T_d + S_2 + S_3T_d + S_4T_d^2 + S_5 \ln(S_6T_d)], \quad (8)$$

where T_d is in kelvin and values of the constants S_0 to S_6 are $S_0 = 1$ Pa, $S_1 = -6096.9385$ K, $S_2 = 21.2409642$, $S_3 = -3.711193 \times 10^2$ K⁻¹, $S_4 = 1.676952 \times 10^{-5}$ K⁻², $S_5 = 2.433502$ and $S_6 = 1$ K⁻¹, respectively. The expanded uncertainty of equation (8) is estimated to be 0.01% of the value in the temperature range from 0 °C to 100 °C [11].

If water vapour is assumed to obey the ideal gas law under laboratory conditions ($t = 20$ °C, $\phi = 50\%$), the total pressure, the partial pressure of water vapour and the mixing ratio are related as

$$r_w = \frac{M_w p_v}{M_a p_a} \approx 0.622 \frac{p_v}{p - p_v}, \quad (9)$$

where the molar masses of water $M_w = 18.015$ g mol⁻¹ and air $M_a = 28.965$ g mol⁻¹ [10].

According to equation (7), the velocity of air is a function of five variables

$$v_3 = g(\dot{m}_{v2}, \rho_{a3}, A_3, r_{w1}, \Delta r_w) \quad (10)$$

and all components are supposed to be uncorrelated. As an additional uncertainty component, the uncertainty due to a non-uniform velocity profile at the test section, δv_3 , is taken into account. Then the combined standard uncertainty of the mixing method can be calculated according to [12]

$$u_c^2(v_3) = \sum_{i=1}^6 \left(\frac{\partial v_3}{\partial z_i} \right)^2 u^2(z_i). \quad (11)$$

An example of the uncertainty calculation can be found in section 3.3.

3. Measurements

3.1. The wind tunnel at the MIKES

The wind tunnel at the MIKES is an open-circulation tunnel using a blower as an air moving apparatus. A schematic drawing of the tunnel is presented in figure 1. The blower is installed upstream of the settling chamber.

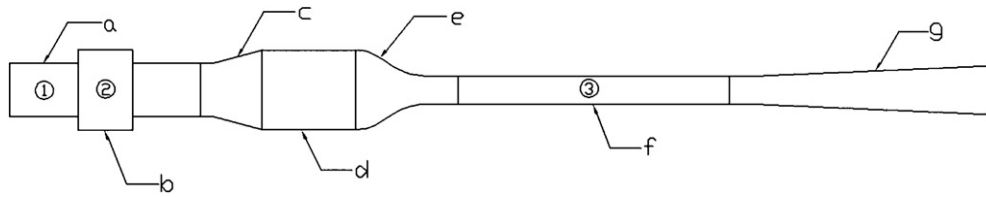


Figure 1. Schematic drawing of the MIKES wind tunnel. The main parts of the tunnel are: (a) humidification unit, (b) blower, (c) wide-angle diffuser, (d) settling chamber, (e) contraction, (f) test section and (g) exit diffuser. The humidification process of air: (1) mixing of feed water vapour and make-up air, (2) dilution of components in the blower and (3) air flow with homogeneous humidity value.

To minimize the cross sectional moisture gradients in the test section of the tunnel, the humidification unit is placed just before the blower. The unit includes an evaporator, a feed water system and a feed water vessel. The vessel is placed on a balance which is controlled by a PC. The water mass flow is determined using a dynamic weighing method, where the mass flow rate is obtained from buoyancy corrected balance indications and corresponding time values. After the humidification unit, feed water vapour is mixed with incoming air in the blower.

A wide-angle diffuser is installed between the blower and a settling chamber. The opening angle of the diffuser is 15° and it is not equipped with screens. The determination of the opening angle is based on the measurement results presented in [13]. After the wide-angle diffuser, air flows to the settling chamber. The diameter of the chamber is 290 mm and it comprises three screens with an open area ratio of 0.64. The diameter of the apertures of the screens is 0.71 mm. A 35 mm thick honeycomb with cells of diameter 3.6 mm is placed after two screens and one screen is set after the honeycomb.

The design of the contraction of the MIKES wind tunnel is based on the studies presented in [14] and [15]. The shape of the contraction is a sixth-order polynomial with a contraction ratio of 7.8. The length of the contraction is 290 mm. After the contraction, there is a straight test section with a length of 1000 mm. The inner diameter of the section is 104 mm.

To minimize the head loss, an exit diffuser is installed after the measurement section. The design of the diffuser is based on [13] and [16]. The opening angle of the diffuser is $2\theta = 5^\circ$ and the area ratio is 3. A quite mild opening angle is used to avoid separation of the boundary layer.

The velocity distribution in the test section was studied with a Pitot-tube. Measurements were made in the directions of the x - and y - axes, both at eleven points. The coordinate system used is presented in figure 2. The first point in the x -axis direction was chosen to be $(x = 2 \text{ mm}, y = 52 \text{ mm})$, i.e., 2 mm from the wall of the pipe and the last one $(x = 102 \text{ mm}, y = 52 \text{ mm})$ was 2 mm from the opposite wall. The other nine points were chosen regularly between the first and last points. Similarly for the y -axis direction, the first measurement point was at a point $(x = 52 \text{ mm}, y = 2 \text{ mm})$ and the last one at a point $(x = 52 \text{ mm}, y = 102 \text{ mm})$. All measurements were done four times at four different velocities: 3.5 m s^{-1} , 7 m s^{-1} , 15 m s^{-1} and 30 m s^{-1} . Averaged velocity distributions are presented in figures 3 and 4 as a function of dimensionless velocity v/v_{\max} , where v_{\max} is the maximum detected velocity. The first and last measurement points are omitted from the figures

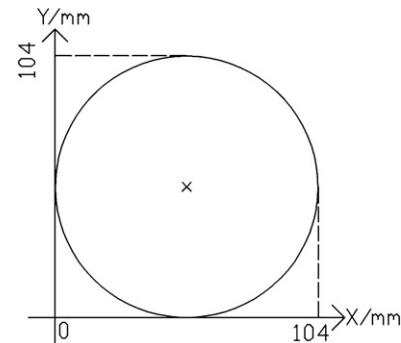


Figure 2. Coordinate system used for studying velocity profiles in the wind tunnel. The direction of air flow is to the figure.

to increase the resolution in a possible measurement area of the test section.

3.2. Measurements

The MM was used for air velocity measurements in the MIKES wind tunnel. The measurement results calculated with equation (7) were compared against calibrated Pitot-tube readings. The dew-point of air before the humidification and at the measurement point was measured with a chilled mirror hygrometer equipped with a three-way valve to switch the air sampling between the inlet and the test section (points 1 and 3 in figure 1). During the measurements, the dew-point data at the inlet of the tunnel were recorded first, then the sampling was switched to the test section. After that the measurement at the inlet was repeated.

The sampling tube presented in figure 5 is a pipe plugged at the top end and equipped with small holes. During measurements, air was sucked through the holes to the dew-point hygrometer using a small pump. With the holes, it was possible to obtain an average dew-point reading from the vertical centre line of the test section. Figure 5 shows also the evaporation unit which includes the feed water supply and evaporator with a heat source.

Two thermistors connected to a digital multimeter were used for air temperature measurements to determine the air density at the measurement point. The air pressure was measured with a barometer and a Pitot-pressure with a micromanometer. The resolution of the manometer was 0.01 Pa, when the pressure difference was smaller than 200 Pa. At higher pressure differences the resolution was 0.1 Pa. The device was calibrated at the MIKES. According to the

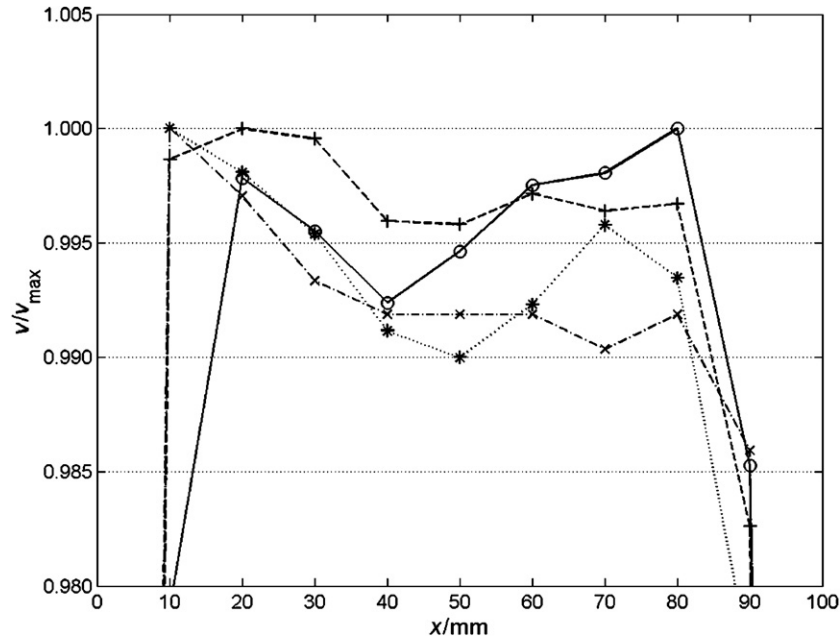


Figure 3. Velocity distribution in the x -axis direction. The solid line with circle markers corresponds to the velocity of 30 m s^{-1} , the dashed line with plus markers to 15 m s^{-1} , the dotted line with asterisks to 7 m s^{-1} and the dash-dot line with crosses to 3.5 m s^{-1} .

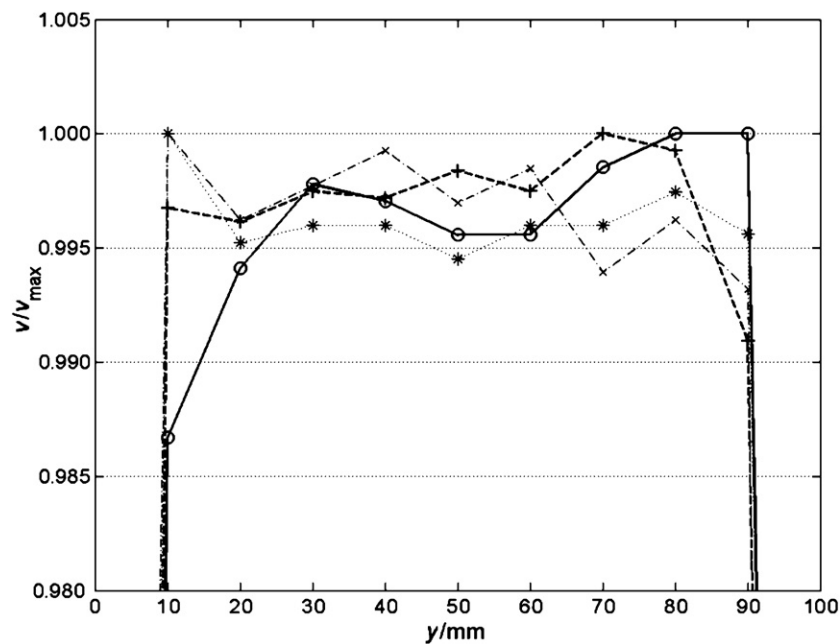


Figure 4. Velocity distribution in the y -axis direction. The solid line with circle markers corresponds to the velocity of 30 m s^{-1} , the dashed line with plus markers to 15 m s^{-1} , the dotted line with asterisks to 7 m s^{-1} and the dash-dot line with crosses to 3.5 m s^{-1} .

calibration certificate, corrections of the micromanometer were less than 1 Pa through the pressure difference range from 0 Pa to 2000 Pa. The same air density value was used both in calculating the air velocity according to equation (7) and according to the Pitot-tube equation

$$v_3 = k \sqrt{\frac{2\Delta p_p}{\rho_{a3}}} \tag{12}$$

In equation (12) k and Δp_p are the calibration coefficient of the Pitot-tube and the average pressure difference between

the static and dynamic pressure sides of the tube during the measurement period, respectively.

Before starting the measurements, the water vessel was filled with distilled water, the electrical heater of the evaporator was switched on and the balance was adjusted. When the temperature of the evaporator was high enough, the feed water pump was started and the rotation speed of the blower was adjusted from the control panel of the frequency converter. The feed water flow was imposed with a needle valve such that a dew-point temperature difference of at least 0.5 K was

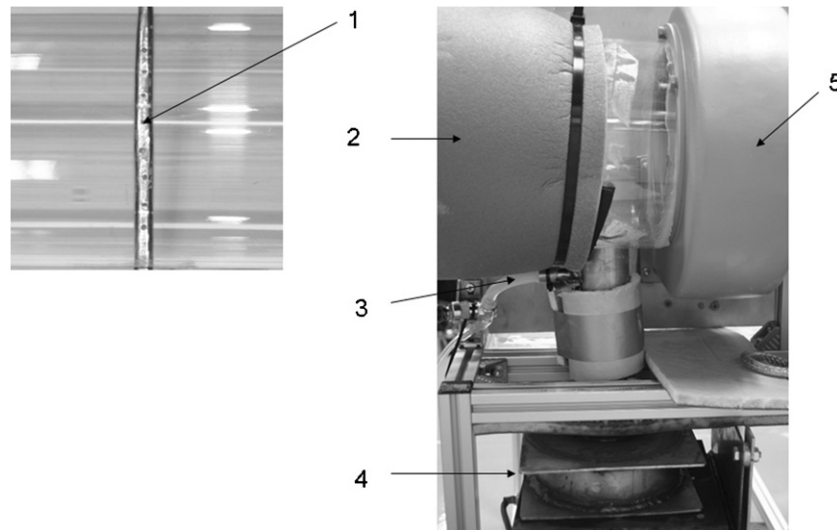


Figure 5. The sampling tube (right) and the evaporation unit without insulation (left). (1) Sampling tube with holes; (2) air inlet and air sampling with the sampling tube; (3) feed water to the evaporator; (4) evaporator with a heat source; (5) blower.

Table 1. Comparison of air velocities measured by the mixing method (MM) and a Pitot-tube.

MM (m s ⁻¹)	U ($k = 2$) (m s ⁻¹)	Pitot (m s ⁻¹)	U ($k = 2$) (m s ⁻¹)	MM – Pitot (m s ⁻¹)	MM – Pitot (%)
5.50	0.2	5.46	0.7	0.04	0.7
10.3	0.4	10.3	1.1	0.00	0.0
21.1	0.8	21.0	2.2	0.07	0.3
29.3	1.6	29.2	3.1	0.13	0.4

obtained between the test section and before the humidification of incoming air.

The Pitot-tube was installed at the centreline of the test section such that the tip of the tube was at a distance of 418 mm from the end of the contraction, as in figure 6. The misalignment was kept as small as possible by using a ruler and visual inspection. Two thermistors were attached symmetrically with the centreline at the same location with the vertical part of the Pitot-tube. Air sampling from the test section to the dew-point hygrometer was realized with a small pump and an averaging sampling tube which was placed at a distance of 700 mm from the end of the contraction. The tube makes multiple samples across the test section, such as an annubar-tube. The minimum distance between the instruments was 200 mm to ensure non-disturbed measurements.

Four measurement points between 5 m s⁻¹ and 30 m s⁻¹ were studied. When the feed water flow was adjusted, the system was allowed to stabilize for 5 min. After the stabilization time, the dew-point temperature readings before humidification were recorded 120 s. Then the sampling line from the test section to the dew-point hygrometer was connected and a 300 s measurement period was started. Readings from the balance, differential pressure gauge, digital multimeter and dew-point hygrometer were recorded. After the measurement period, the dew-point measurement before humidification was repeated. In calculations the dew-point temperature before the humidification was an average of readings taken just before and after the measurement period.

The exit diffuser reduces the static pressure in the test section. For that reason, the barometric pressure in the test

section is smaller than the ambient one, where the dew-point hygrometer operates. When the partial pressure of water diminishes, the dew-point temperature decreases. This is taken into account in determining the partial pressure of water vapour in the test section by solving the equation

$$p_{v3} = \frac{p - \Delta p}{p} p'_{v3}, \quad (13)$$

where Δp and p'_{v3} are the difference between ambient and test section pressures and the water vapour pressure calculated with equation (8) using ambient pressure, respectively.

3.3. Results

A comparison of the results obtained by the mixing method and Pitot-tube is presented in table 1. An example of an uncertainty budget at an air velocity of 10 m s⁻¹ is presented in table 2. In table 1, U and k are the expanded uncertainty and corresponding coverage factor, respectively. In table 2, x_i , c_i and $u(x_i)$ are the input estimate, sensitivity coefficient and standard uncertainty of the estimate x_i , respectively. The obtained uncertainty for the mass flow of humidification water is based on the calculations presented in [17, 18], taking also into account two additional components due to water condensation to the surfaces of the blower and evaporation of water from the feed water vessel. The condensation is approximated to be 0.5% of water mass flow and evaporation was measured to be 10 $\mu\text{g s}^{-1}$, resulting in a combined standard uncertainty $u(\dot{m}_{v2}) \approx 1\%$. For air density determination, an uncertainty of 0.01 kg m⁻³ was assumed. The diameter of the

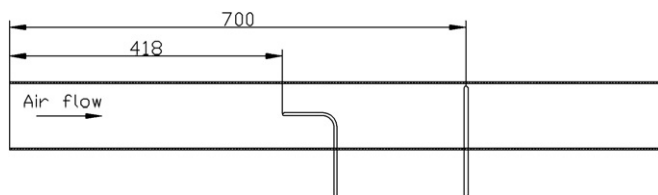


Figure 6. Placing of Pitot- and air sampling tubes in the test section. The tip of the Pitot-tube is installed at a distance of 418 mm and the sampling tube at a distance of 700 mm from the end of the contraction.

Table 2. Example of an uncertainty budget for mixing method at an air velocity of 10 m s⁻¹.

x_i	c_i	Units	$u(x_i)$	Units	$c_i u(x_i)$
m_{v2}	414 625	m kg ⁻¹	2.5×10^{-7}	kg s ⁻¹	0.10
ρ_{a3}	8.9	m ⁴ /(kg s)	0.01	kg m s ⁻³	0.09
A_3	1228	m ⁻¹ s ⁻¹	1.8×10^{-5}	m ²	0.02
r_{w1}	10		1.5×10^{-5}		0.00
Δr_w	43248		2.9×10^{-6}		0.13
δ_{v3}	1		0.09	m s ⁻¹	0.09
			u_c		0.21
			$U (k = 2)$		0.42

test section was calculated as the mean of 30 separate values measured with a Vernier calliper. The uncertainty value for the cross-section area was obtained by taking into account the standard deviation of the mean, resolution of the Vernier calliper and the uncertainty due to the elasticity of a material of the test section giving a value of 18 mm².

In equation (7), the absolute value of r_{w1} appears in the numerator and the difference Δr_w in the denominator. The uncertainty estimate for r_{w1} takes into account the standard deviation of the mean and calibration uncertainty of the

dew-point hygrometer. The uncertainty of Δr_w was calculated from the sensitivity, non-linearity and reproducibility of the dew-point hygrometer.

The evaporation process in the humidification unit is more pulsed than smooth in its nature. That behaviour can be seen as a variation in the dew-point temperature. The water flows to the unit droplet by droplet and peaks are consequences of sudden vaporization of these droplets. Figure 7 illustrates a typical example of this variation during one 300 s measurement period. The dew-point temperature varied between 9.57 °C and 9.82 °C, giving the maximum observed fluctuation of 0.25 °C.

4. Discussion and conclusions

A new mixing method with uncertainty analysis for linking the air velocity to the national standards of mass and time is presented in this paper. The method can be applied to air velocity measurement in wind tunnels. It is based on humidification of air flowing into the tunnel with a known mass flow of water vapour. Then the air mass flow can be pronounced as a function of humidification water mass flow. Part of the traceability in the MM comes from the dew-point standard. However, this branch can be assumed to be insignificant, because the linearity of the dew-point hygrometer is essential in that application, not the absolute value. By measuring the mixing ratios of air before and after the humidification process and determining the density of air and measuring the cross sectional area of a test section of a wind tunnel, the air velocity can be calculated. The method is compared against a Pitot-tube in the wind tunnel at the MIKES. To find out the metrological competence of the method, the same Pitot-tube was calibrated at the University of

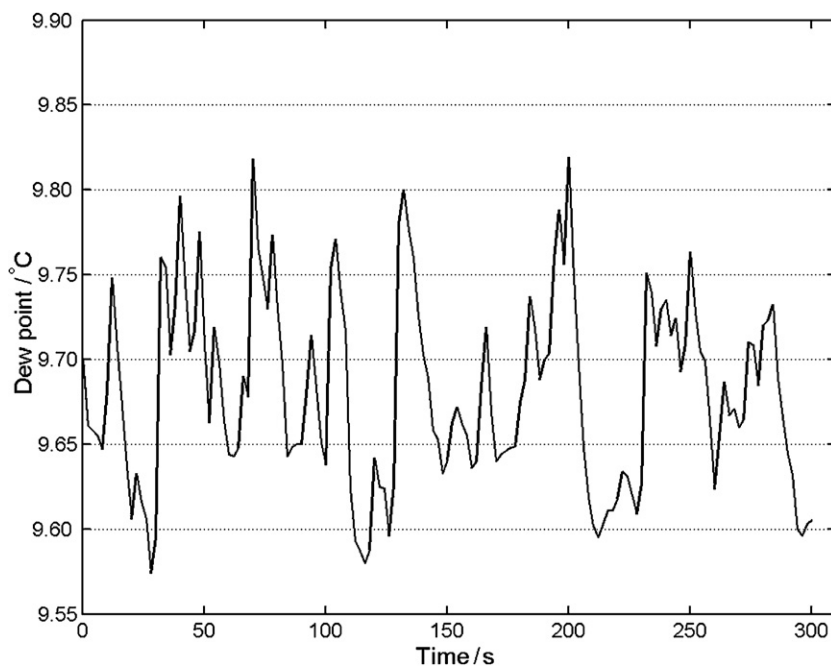


Figure 7. The fluctuation of the dew-point temperature during one 300 s measurement period.

Tartu against a high accuracy Pitot-tube. As can be seen from the results, they will differ by only 0.7% at the maximum.

Humidity measurements were done using a chilled mirror dew-point hygrometer. In this way, it was possible to decrease the uncertainty of absolute humidity measurement and simplify the calculation process. The capacitive humidity probes were also tested, but their stability and linearity were not good enough for such demanding measurements. The humidification process together with the blower increases the temperature of flowing air at the test section under 1 K. As can be seen from the uncertainty budget for the mixing method, the difference between dew-point temperatures for calculating Δr_w is the most dominating uncertainty component over the whole measurement range.

The Reynolds numbers in the test section of the wind tunnel at the studied velocities were between 27×10^4 and 20×10^5 . So, the flow was turbulent in its nature. The maximum deviation between the highest and lowest velocity in the test section at the cross-sectional area of interest was 1.7% in the x -axis direction and 1.4% in the y -axis direction.

The mixing method gives a novel and quite simple way to establish a traceability link between air velocity measurements and the national standards of mass and time. Based on the study of sensitivity coefficients, most attention should be paid to the water mass flow and air dew-point temperature measurements to improve the accuracy of the measurement system. Smoothing of the evaporation process is needed for the decrease of dew-point temperature fluctuations.

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