Uncertainty Evaluation of Fluid Density at High Air Speed Standard in NMIJ

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Abstract

The National Metrology Institute of Japan (NMIJ) maintains high air speed standard and its calibration facility is capable of a relative expanded uncertainty (k = 2) of 0.63 % in the air speed range 40 m/s to 90 m/s. The model equation for measurement uncertainty in the high air speed calibration wind tunnel, which is the working standard, employs a method that cancels out the density term of the fluid. This is due to the fact that the density on the wind tunnel and DUT side is considered to be the same, i.e., the air speed values on the wind tunnel and DUT side are based on the same Bernoulli's principle. Therefore, the calibration environment of this standard is registered in the KCDB (CIPM MRA database) as ambient, which is independent of temperature and pressure changes throughout the year. However, there is a need to develop a calibration method for anemometers which are not based on Bernoulli's principle, as calibration targets. In this presentation, the reproducibility of air speed values in the wind tunnel is experimentally discussed, especially in the calibration environment, as the density of air changes throughout the year. In addition, the relative uncertainty of the density due to the difference of air density derivation formulas will be compared. Finally, the measurement uncertainty with the corrective coefficient of the anemometer under calibration due to the density change of air will be discussed.

1. Introduction

The National Metrology Institute of Japan (NMIJ) maintains high air speed standard and its calibration facility is capable of a relative expanded uncertainty (k = 2) of 0.63 % in the air speed range 40 m/s to 90 m/s [1]. The model equation for measurement uncertainty in the high air speed calibration wind tunnel, which is the working standard, employs a method that cancels out the density term of the fluid. This is due to the fact that the density on the wind tunnel and DUT side is considered to be the same, i.e., the air speed values on the wind tunnel and DUT side are based on the same Bernoulli's principle. Therefore, the calibration environment of this standard is registered in the KCDB (CIPM MRA database) as ambient, which is independent of temperature and pressure changes throughout the year [2].
However, there is a need to develop a calibration method for ultrasonic anemometers, thermal anemometers, and Doppler lidars, for which the measurement principle of the DUT is not based on Bernoulli's principle, as calibration targets. In such cases, the handling of the density term of the fluid becomes a problem. At present, we believe that there are three main issues to be sorted out in the uncertainty analysis of fluid density in the high air speed calibration wind tunnels. The first is the evaluation of the time variation of the density between measurements of a single point of air speed. The second is due to the environmental conditions of the test room where the wind tunnel is installed. This one can be read as the change in air density throughout the year. Third, although related to the two items mentioned above, the evaluation of the equation for the calibration of air density. The high air speed standard uses the equation (C.29) in JIS B 7609 (2008) [3] in the calculation of air density. This equation has high sensitivity to air temperature fluctuations compared to fluctuations in air pressure and humidity. The applicable range of relative uncertainty that can be regarded as a fixed value is specified as being greater than 90 kPa and less than 110 kPa, higher than 10 ℃ and lower than 30 ℃, and a related humidity of less than 80 %. On the other hand, although the equation to accurately calculate the density of moist air is specified as CIPM-2007 [4], it has not been sufficiently verified for comparison with this one.
In this presentation, the reproducibility of air speed values in the wind tunnel is experimentally discussed, especially in the calibration environment, as the density of air changes throughout the year. In addition, the relative

uncertainty of the density due to the difference of air density derivation formulas will be compared. Finally, the measurement uncertainty with the corrective coefficient of the anemometer under calibration due to the density change of air will be discussed.

Nomenclature

C_{pit}	Corrective coefficient of a Pitot static tube from single measurement [-]	v_{pit}	Air speed measured by Pitot-static tube [m/s]
C_{WT}	Corrective coefficient of the wind tunnel [–]	v_{WT}	Reference air speed by the wind tunnel [m/s]
hr	Related humidity [%]	x_v	Mole fraction of water vapor [-]
M_a	Molar mass of dry air[g/mol] (= 28.96546 $\times 10^{-3}$ [kg/mol])	Z	Compressibility factor [-]
M_v	Molar mass of water[g/mol]	ΔP_{pit}	Dynamic pressure measured by the Pitot-static tube [Pa]
p	Atmospheric pressure [Pa]	ΔP_{WT}	Differential pressure between the nozzle inlet and outlet [Pa]
p_{jis}	Pressure calculated by Equation (2) [mbar or hPa]	ρ	Fluid density at the wind tunnel [kg/m^3]
R	Molar gas constant [J/mol・K] (= 8.314472(15) [J/mol・K])	ρ_{jis}	Fluid density calculated by Equation (2) [kg/m^3]
T_{K}	Temperature of the measurement area [K]	ρ_{CIPM}	Density of moist air calculated by Equation (3) [kg/m^3]
T_{C}	Temperature of the measurement area [℃]		

2. Additional sections and subsections

The experiment of the high air speed calibration wind tunnel was conducted at Tsukuba North Site in National Institute of Advanced Industrial Science and Technology. The schematic diagram and picture of the wind tunnel are shown in Figure 1. The wind tunnel is Eiffel type, and the measurement area is open area. The circle jet of diameter 100 mm is produced from the nozzle outlet as the upstream side of the measurement area. Environmental data of atmospheric pressure, temperature, and related humidity for five minutes with stable jet were measured every month from April 2021 to June 2022. The environmental data at the measurement area of the wind tunnel during the measurement period are shown in Figure 2 to Figure 4. Measurement devices for measurement of fluid density are HMT333 thermo-hydrometer (Vaisala Corporation) and MT210 atmospheric gauge (Yokogawa Electric Corporation). Because the heat of the blower is added to the jet produced by the wind tunnel, the jet become steady at a temperature that balances the heat of the blower with the room temperature. The fluid density is calculated by the thermally balanced temperature.

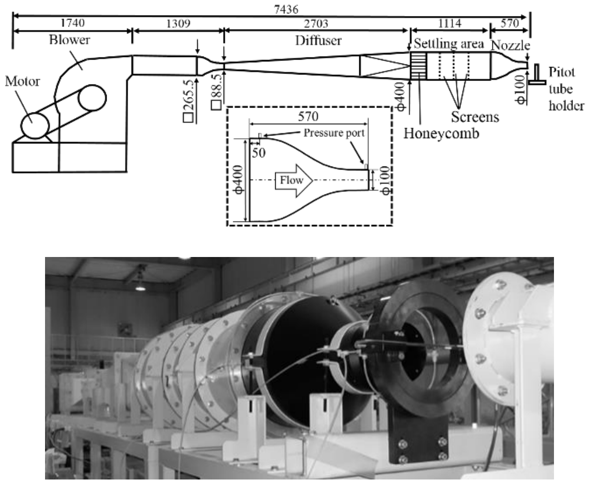

Figure 1: Schematic diagram and picture of the wind tunnel.

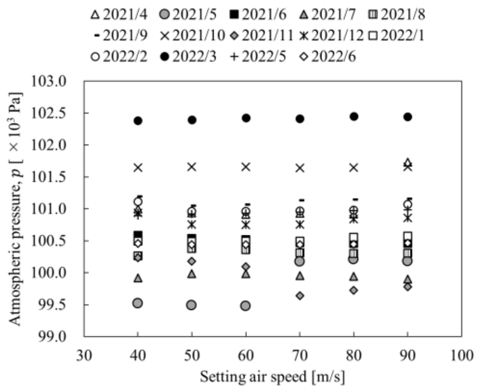

Figure 2: Atmospheric pressure at the wind tunnel.

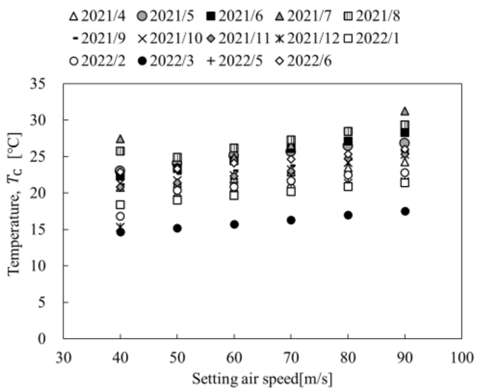

Figure 3: Temperature at the wind tunnel.

Straight type ϕ3 Pitot-static tube was placed at the Pitot tube holder and was aligned in the flow direction. The total pressure hole of the tube was located at the center of the nozzle exit. The air speed at the nozzle exit was varied as 40 m/s, 50 m/s, 60 m/s, 70 m/s, 80 m/s, and 90 m/s. The corrective coefficients of the tube were calculated by the differential pressure between the nozzle inlet and outlet, the differential pressure of the tube, and the corrective coefficient of the wind tunnel.

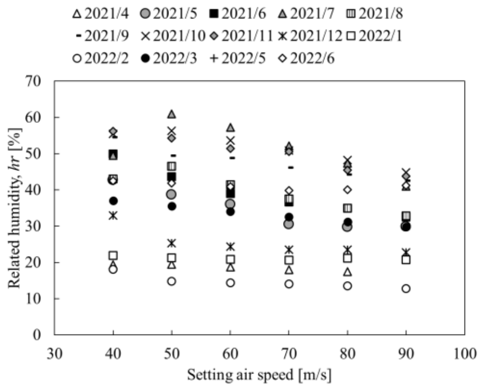

Figure 4: Related humidity at the wind tunnel.

3. Result

3.1 Time series variation of the fluid density

In this standard, the air speed of single measurement point is calculated by the differential pressure during sixty seconds, when the jet is stable and thermally balanced. The parameter for decision of the data interval of the 60 seconds is temperature. The criterion of the temperature is that the temperature variation during the 60 seconds is under ±0.1 ℃. In the time series interval selected by this criterion, because the related humidity is linked to the temperature, so the related humidity hardly changes. The atmospheric pressure also hardly changes because the 60 seconds is too short to change the atmospheric pressure. Thus, it is cleared that the time series variation of the fluid density at single measurement point is negligible small.

3.2 Calculation of fluid density

The model equation for measurement uncertainty in the high air speed calibration wind tunnel employs a method that cancels out the density term of the fluid. The corrective coefficient of the Pitot-tube as DUT which is calibrated by the wind tunnel [1] is calculated as follows:

$$C_{\mathrm{pit}} = \frac{v_{\mathrm{WT}}}{v_{\mathrm{pit}}} = C_{\mathrm{WT}} \frac{\sqrt{\frac{\Delta P_{\mathrm{WT}}}{\rho}}}{\sqrt{\frac{\Delta P_{\mathrm{pit}}}{\rho}}} = C_{\mathrm{WT}} \sqrt{\frac{\Delta P_{\mathrm{WT}}}{\Delta P_{\mathrm{pit}}}} \quad (1)$$

The fluid density at the measurement area in the wind tunnel is calculated by the equation (C.29) in [3], as follows:

$$\rho_{\mathrm{jis}} = \frac{\{0.34848 p_{\mathrm{jis}} - 0.009(hr) \times \exp(0.061 T_{\mathrm{C}})\}}{(273.15 + T_{\mathrm{C}})} \quad (2)$$

This equation has relative uncertainty of 2×10^{-4} when 900 < p_{jis} < 1100, 10 < t < 30, hr < 0.8.
Next, the fluid density equation of [4] as follows:

$$\rho_{\mathrm{CIPM}} = \left(\frac{pM_a}{ZRT}\right) \times \left\{1 - x_v\left(1 - \left(\frac{M_v}{M_a}\right)\right)\right\} \quad (3)$$

The recommended ranges of temperature and pressure are 600 hPa ≦ p ≦ 1100 hPa and 15 < t < 27.
The fluid density which is calculated by equation (2) and (3) using the experimental data at the wind tunnel is shown in Figure 5.

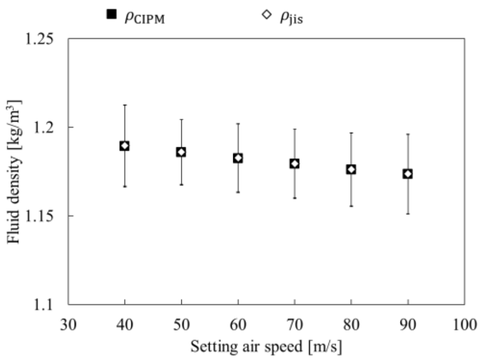

Figure 5: Comparison of fluid density.

The fluid density values are average, and the error bars are standard deviation of the fluid density throughout the year. Both of standard deviation of the fluid density are under 0.03 kg/m³ at all setting air speed range. Both of average fluid density are almost same. Therefore, it doesn't matter which equation we use.

3.3 Fluid density and corrective coefficient

We discuss about the fluid density calculated by Equation (2). In summer season, the fluid density is about 1.15 kg/m³ because of high room temperature. On the other hand, in winter season, the fluid density is about 1.25 kg/m³ because of low room temperature. From the data, there are difference of ±0.05 kg/m³ throughout year. Besides, when the setting air speed is increased, the amount of heat exhausted from the blower is increased and the fluid density is decreased. On some measurement days, the results were indicated that the increase in the setting air speed was not proportional to the decrease in the fluid density. These reasons are considered that the measurement days are over two days, and the measurement order of the setting air speed is not select the descending order from 90 m/s but another order such as ascending order from 50 m/s. Therefore, in order to minimize the change in the balance point between the setting air speed and the fluid density, calibration at all setting air speeds should be performed in one day, and the measurement order should be from 90 m/s to descending order. Until now, the calibration target was only the Pitot tube, so we didn't anticipate changes in the balance point due to the measurement procedure. However, it was revealed that it is important to unify the measurement procedure and understand the fluid density change due to the heat generation of the blower in advance form the viewpoint of establishing the standard in the future.

Next, the corrective coefficients of the Pitot-static tube throughout year are shown in Figure 6 to Figure 11.

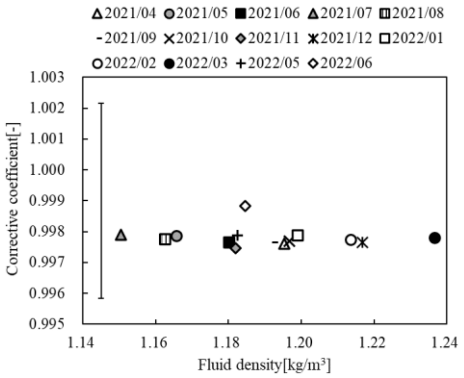

Figure 6: Corrective coefficient of Pitot-static tube at 40 m/s.

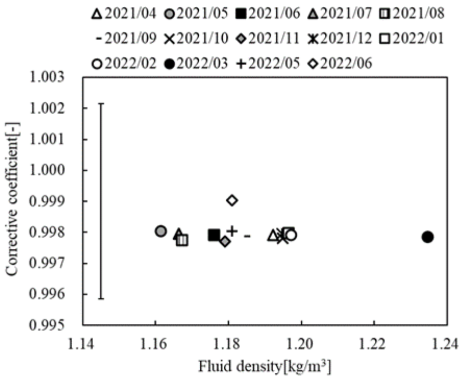

Figure 7: Corrective coefficient of Pitot-static tube at 50 m/s.

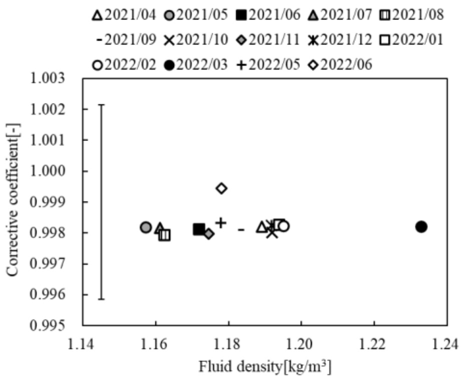

Figure 8: Corrective coefficient of Pitot-static tube at 60 m/s.

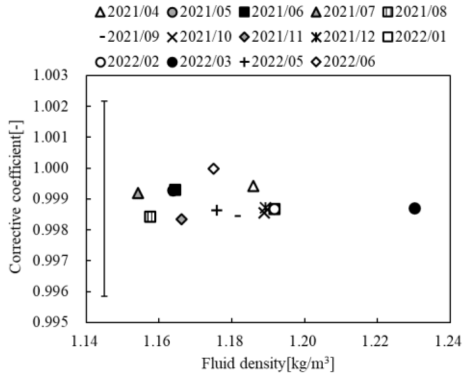

Figure 9: Corrective coefficient of Pitot-static tube at 70 m/s.

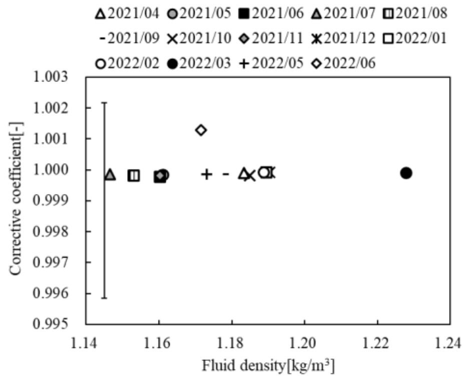

Figure 10: Corrective coefficient of Pitot-static tube at 80 m/s.

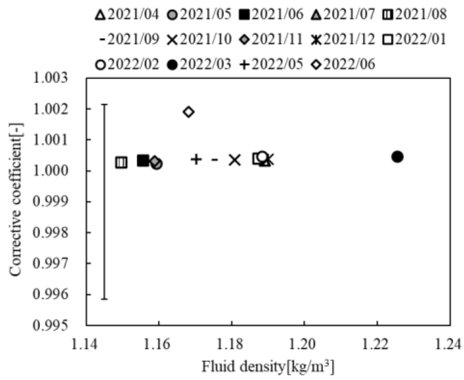

Figure 11: Corrective coefficient of Pitot-static tube at 90 m/s.

Error bars indicate standard uncertainties (k = 1) 0.316 % of the high air speed standard at NMIJ. The corrective coefficients are within the error bars at all setting air speed setting and all the fluid density. Therefore, it was revealed that the variation of the corrective coefficients is small compared with the variation of the fluid density throughout year. In spite of the same fluid density value, there were cases where the corrective coefficients were up to 0.15 % higher than the average corrective coefficients such as Figure 9. This reason was the ratio of the difference pressure of the wind tunnel and the differential pressure of the Pitot-static tube was also change up to 0.15 %. This cause is considered that the reproducibility by attaching and detaching the Pitot-static tube and deflection of the pressure tube for the Pitot-static tube.

3.4 Uncertainty analysis of fluid density

In the case of adopting Equation (2), the sensitivity coefficients of the fluid density for atmospheric temperature, related humidity, and temperature are indicated as follows:

$$\frac{\partial \rho_{\mathrm{jis}}}{\partial p_{\mathrm{jis}}} = \frac{0.34848}{(273.15 + T_{\mathrm{C}})} \tag{4}$$

$$\frac{\partial \rho_{\mathrm{jis}}}{\partial hr} = \frac{0.009 \times \exp\,(0.061 T_{\mathrm{C}})}{(273.15 + T_{\mathrm{C}})} \tag{5}$$

$$\frac{\partial \rho_{\mathrm{jis}}}{\partial T_{\mathrm{C}}} = \frac{\{-0.009(hr) \times 0.061 \times \exp(0.061 T_{\mathrm{C}}) \times (273.15 + T_{\mathrm{C}})\}}{(273.15 + T_{\mathrm{C}})^2} - \frac{\{0.34848 p_{\mathrm{jis}} - 0.009(hr) \times \exp\,(0.061 T_{\mathrm{C}})\}}{(273.15 + T_{\mathrm{C}})^2} \tag{6}$$

The sensitivity coefficients of the fluid density which substitute the environmental condition of the wind tunnel throughout year for Equation (4) to Equation (6) is shown in Figure 12.

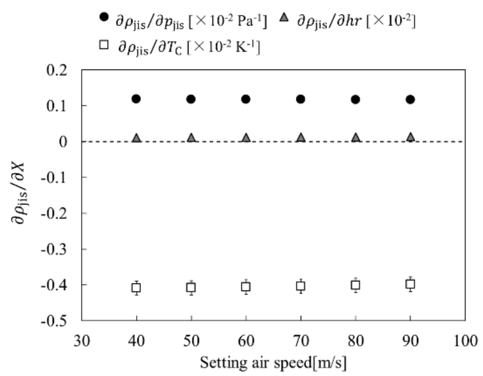

Figure 12: Sensitivity coefficient of fluid density for conditions.

Each error bar indicates variation of the sensitivity coefficient throughout year. Therefore, each sensitivity coefficient is small and almost same for each setting air speed. The value and variation of the sensitivity coefficient of the fluid density for temperature is larger than the other sensitivity coefficients. It was cleared that the temperature is more important than the other parameters and the fluid density is decreased when the temperature is increased.
Next, uncertainty analysis of atmospheric pressure, related humidity, and temperature will be explained in the presentation.

4. Uncertainty for each measurement principle

We discuss the calculation of uncertainty for the anemometer which is not based on Bernoulli's principle such as ultrasonic, thermal, and Doppler-lidar type. Uncertainty accompanies the corrective coefficient of the indicated air speed which is measured by anemometers. In this chapter, the evaluation policy and future work for the uncertainty of indicated air speed by the anemometer which is not based on Bernoulli's principle are indicated.
When fluid density correction is included at the calculation process of the indicated air speed by anemometer, the uncertainty of fluid density in the indicated air speed is zero. On the other hand, when fluid density correction is not included at the calculation process of the indicated air speed by anemometer, there are two plans. First, the variation of the indicated air speed by the variation of the fluid density at the wind tunnel is added as the uncertainty of DUT side. Second, the corrective coefficient of the indicated air speed is indicated with the fluid density during the calibration. There are two plan as future work. First, the air speed measurement by ultrasonic and thermal type anemometer at the wind tunnel. Second, the evaluation of the blockage effect for the geometry of the sensor of the ultrasonic and thermal type anemometer.

5. Conclusion

The measurement of the fluid density by the environmental condition throughout year and the evaluation of the fluid density calculation equations were conducted at the high air speed calibration wind tunnel in NMIJ. It was confirmed that the fluid density throughout year changes $\pm$0.05 kg/m^3 from the average and the fluid density calculated by two equations is overlapped in the range of the variation at all the setting air speed. Next, the repeatability of the air sped by the wind tunnel was experimentally evaluated using straight type ϕ3 Pitot-static tube. The variation of the corrective coefficients was small compared with the variation of the fluid density throughout year. Finally, the uncertainty analysis plan and the future work was indicated about the uncertainty of the fluid density for the indicated air speed by the anemometer which is not based on Bernoulli's principle.

References

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