Collaboration between TISTR and NIMT: An application of the pressure metrology in an air speed measurement

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Abstract. This paper describes a collaboration between Thailand Institute of Science and Technological Research (TISTR) and National Institute of Metrology Thailand (NIMT) in an application of a differential pressure measurement to an air speed measurement. The aim of the collaboration is to link the measurement of an air speed by a pitot static tube anemometer at TISTR to the measurement of a differential pressure at NIMT. Upon completing the project, TISTR’s pitot tube anemometer is traceable to NIMT’s force balance piston gauge. TISTR’s pitot tube anemometer in combination with its Eiffel-type wind tunnel can be employed as a calibration system for an anemometer. The result of the collaboration leads to a lower cost of maintaining TISTR’s traceability in air speed measurement.

1. Introduction

Recently, a demand for the calibration of an anemometer has been continuously increasing due to high growth in aerodynamics, development of a small aerial vehicle and calibration activities in the country. The aforesaid demand has become indispensable. The request to both Thailand Institute of Science and Technological Research (TISTR) and National Institute of Metrology Thailand (NIMT) is not only for a calibration service, but also an aid to establish their own systems for testing and calibration of an anemometer.

The aims of the collaboration are to implement an adequate method with lowest resource requirements for an anemometer testing and calibration at TISTR as well as to link an air speed traceability chain in Thailand to the available differential pressure measurement at NIMT.

2. System specification

The following sections describe specifications of TISTR’s air speed system.

2.1. Air speed standard

The pitot tube anemometer composes of one pitot static probe and four differential pressure transmitters from Westenberg Engineering to measure a total pressure and a static pressure at high input port and
low input port respectively. The measurement range of the transmitters are 25 Pa, 100 Pa, 400 Pa and 1.6 kPa with 0.4% accuracy.

2.2. Wind tunnel
The wind tunnel is an Eiffel-type wind tunnel which is an open circuit wind tunnel with suction configuration as shown in figure 1. The open jet test section has a diameter of 320 mm. The operating range of the wind tunnel is 0.3 m/s to 40 m/s. The turbulent intensity is claimed to be less than 0.8%.

![Figure 1. Air speed standard at TISTR.](image)

3. Flow characteristic
Two important flow characteristics inside the test section which are a flow-uniformity and a turbulent-intensity were determined by the manufacturer of the wind tunnel. The measurements were performed by the use of a laser doppler anemometer with an uncertainty less than 0.1% of reading.

3.1. Air speed standard
Table 1 shows the values of non-uniformity at each selected speed in percentage.

| Nominal Velocity (m/s) | Average Velocity (m/s) | Non Uniformity (m/s) | Non Uniformity (%) |
|------------------------|------------------------|---------------------|-------------------|
| 5                      | 4.9544                 | 0.0103              | 0.2024            |
| 10                     | 9.9504                 | 0.0227              | 0.2219            |
| 20                     | 19.8482                | 0.0367              | 0.1795            |
| 40                     | 39.5684                | 0.0853              | 0.2092            |
3.2. Turbulent intensity

Table 2 shows the maximum values of turbulent intensity at each selected speed in percentage.

| Nominal Velocity (m/s) | Average Velocity (m/s) | Turbulent Intensity (m/s) | Turbulent Intensity (%) |
|------------------------|------------------------|---------------------------|-------------------------|
| 5                      | 5.106                  | 0.0199                    | 0.39                    |
| 10                     | 10.220                 | 0.0347                    | 0.34                    |
| 20                     | 20.438                 | 0.0695                    | 0.34                    |
| 40                     | 40.756                 | 0.0171                    | 0.42                    |

The values of non-uniformity and turbulent intensity shown in table 1 and table 2 are all met the requirements of ASTM D 5096-01, ASTM 6011-96, ISO 17713-1 and ISO 16622 which require that the values shall be less than 1% [1-4].

4. Calibration standard and traceability

The measurement method used in the project was inspired by those employed by the Korean Institute of Standards and Science (KRISS) in the APMP Air Speed Key Comparison (APMP.M.FF-K3). In the comparison, pitot anemometer was utilized by Dr. Yong Moon Choi from KRISS. The comparison results were compatible with those obtained from a laser Doppler anemometer [5]. Therefore, pitot anemometer was used in this wind tunnel as a calibration standard. The calculation and the uncertainty analysis were adopted from those employed by KRISS in the comparison. The measurement is traceable to the differential pressure standard at National Institute of Metrology Thailand (NIMT) as shown in figure 2.

According to ISO3966, the local velocity of a fluid in a steady flow without transverse velocity gradient or turbulence is given by the expression [6]

\[ v = \alpha (1 - \varepsilon) \sqrt{\frac{2\Delta p}{\rho}} , \]  

where the compressibility effect \((1 - \varepsilon)\) at low Mach number is determined by

\[ (1 - \varepsilon) \approx \sqrt{1 - \frac{1}{2\gamma} \frac{\Delta p}{\rho} + \frac{\gamma - 1}{6\gamma^2} \left( \frac{\Delta p}{\rho} \right)^2} , \]  

where \(\gamma\) is the ratio of specific heat capacities, \(\rho\) is the local density of the fluid, \(\Delta p\) is the differential pressure indicated by the Pitot tube, and \(\alpha\), which is the calibration factor of the Pitot tube, is equal to 1.0015±0.002. To ensure that the above equations are valid, the Reynolds number shall not be less than 200 (equals to the operating velocity of 0.034 m/s for this wind tunnel at 25°C sea level).

In a calibration of an anemometer in a wind tunnel using a pitot tube as a standard, the turbulent intensity and the flow uniformity shall be taken into account. Equation (1) might then be written as follows [7]

\[ v_{STD} = \alpha (1 - \varepsilon) \sqrt{\frac{2\Delta p}{\rho} + tu + \Delta v} , \]  

where \(tu\) is the turbulent intensity and \(\Delta v\) is the velocity deviation caused by the measurement location. The UUC’s measurement error \((E_{UUC})\) is given by the expression
\[ E_{UUC} = (v_{UUC} - v_{STD}) + \delta v_{UUC} + \delta v_{STD}, \]  

(4)

Where \( v_{UUC} \), \( \delta v_{UUC} \), and \( \delta v_{STD} \) are the reading UUC air speed, the correction of UUC resolution/fluctuation and the correction of the standard respectively.

Figure 2. Differential pressure standard at NIMT.

5. Uncertainty of measurement

The uncertainty of the standard velocity, \( v_{STD} \), in equation (3) is expressed as follows [7]

\[
\begin{align*}
    u_i(v_{STD}) = \sqrt{ & c_{\alpha}^2 u^2(\alpha) + c_{1-\alpha}^2 u^2(1-\varepsilon) + c_{\Delta p}^2 u^2(\Delta p) + c_{\rho}^2 u^2(\rho) + \\
    & + c_{\tau}^2 u^2(\tau) + c_{\Delta v}^2 u^2(\Delta v)}
\end{align*}
\]

(5)

where \( u_i \) is the uncertainty due to a component \( i \) and its sensitivity coefficient, \( c_i \). Table 3 shows an example of the uncertainty budget of \( v_{STD} \) for a calibration at 40.71 m/s.

| \( y_i \) | \( x_i \) | \( u_i \) | Prob. Dist. | \( c_i \) | \( |c_i u_i| \) |
|---|---|---|---|---|---|
| \( \alpha \) | 1.0015 | 2.00E-3 | R | 4.06E+1 | 4.06E-2 |
| \( (1-\varepsilon) \) | 0.9976 | 5.50E-8 | N | 4.08E+1 | 2.25E-6 |
| \( \Delta p \) (Pa) | 980 | 4.00E+0 | N | 2.08E-2 | 4.80E-2 |
| \( \rho \) (kg/m³) | 1.181 | 5.90E-3 | R | -1.72E+1 | 5.09E-2 |
| \( tu \) (m/s) | 0 | 1.71E-1 | N | 1 | 1.71E-1 |
| \( \Delta v \) (m/s) | 0 | 8.53E-2 | N | 1 | 8.53E-2 |
| \( v_{STD} \) | 40.71 | | | | 2.08E-1 |

Expanded Uncertainty (\( U \)) 4.16E-1
The expanded uncertainty of $v_{\text{STD}}$ is 0.42 m/s or 1.02% at 40.71 m/s. The coverage factor is 2 at approximately 95% of confidence level.

The uncertainty of the calibration, $E_{\text{UUC}}$, in equation (4) is expressed as follows

$$u_c(E_{\text{UUC}}) = \sqrt{c_{v_{\text{UUC}}-v_{\text{STD}}}^2 (v_{\text{UUC}} - v_{\text{STD}})^2 + c_{\delta v_{\text{UUC}}}^2 u_c^2 (\delta v_{\text{UUC}})^2 + c_{\delta v_{\text{STD}}}^2 u_c^2 (\delta v_{\text{STD}})^2},$$

where $u_c(i)$ is the uncertainty due to a component $i$ and its sensitivity coefficient, $c_i$.

### Table 4. Uncertainty budget of the calibration result.

| $y_i$ | $x_i$ | $u_i$ | Prob. Dist. | $c_i$ | $|c_i u_i|$ |
|-------|-------|-------|-------------|-------|-----------|
| $v_{\text{UUC}} - v_{\text{STD}}$ | -0.586 | 5.50E-8 | N | 1 | 5.50E-8 |
| $\delta v_{\text{UUC}}$ | 0 | 7.50E-2 | R | 1 | 4.33E-2 |
| $\delta v_{\text{STD}}$ | 0 | 2.08E-1 | R | -1 | 2.08E-1 |

Table 4 shows an example of the calibration result for a calibration at 40.71 m/s. The calibration and measurement capability (CMC) are presented in table 5.

### Table 5. Uncertainty budget of the calibration result.

| Velocity | Unit | $v$ (m/s) | 5 | 10 | 20 | 40 |
|----------|------|-----------|---|----|----|----|
| CMC | m/s | 0.37 | 0.21 | 0.47 | 0.43 |
| % | 7.4 | 2.1 | 2.4 | 1.1 |

### 6. Conclusion and perspective

An adequate and cost-effective method has been implemented to TISTR’s air speed standard. The method is based on a measurement of a total pressure and a static pressure using a pitot tube. At the maximum operating speed, the uncertainty of the system was estimated to be 1.1% with the coverage factor of 2 at approximately 95% confidence level. This uncertainty might be possibly improved by using more accurate differential pressure standard.

Finally, the airspeed calibration standard is traceable to a differential pressure measurement at NIMT and the method is ready to implement to any secondary laboratory in Thailand.

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