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The effect of flow approaching angle on the velocity measurement using bi-directional velocity probe

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Abstract

As a preliminary study for estimating the measurement uncertainty and optimal design of bi-directional velocity probe used in fire testing application, the present study has been conducted to examine the effect of Reynolds number and flow approaching angle on the measurement uncertainty of bi-directional probe. Additionally, the CFD calculation has been performed to investigate the flow field near the bi-directional probe and analyze the flow characteristics with the flow approaching angle. The experimental result shows that the measured probe constant for high Reynolds number is slightly higher than that of McCaffrey and Heskestad while it is in good accordance with Sette's previous result. For the case of Re=3,400, the angular sensitivity between -45° and 45° well matched the previous work of McCaffrey and Heskestad and the maximum angular sensitivity reached 10% comparing to the case of the flow approaching angle of 0°. The angular sensitivity increased with increasing Reynolds number and the maximum angular sensitivity was observed at flow approaching angle of 30°. From the CFD analysis, asymmetric wake flow was observed at the rear side of bi-directional probe at flow approaching angle of 30°, and the dynamics pressure variation inside the probe hole may affect the angular sensitivity of velocity measurement using bi-directional probe. The present study focuses on the measurement uncertainty and design optimization of bi-directional probe and can contribute to improving the reliability of fire measurement.

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Keywords: Velocity measurement; Bi-directional probe; Fire testing; Flow approaching angle

Nomenclature

\(k_p\) probe constant
\(D\) diameter of bi-directional probe (mm)
\(L\) length of bi-directional probe (mm)
\(P\) pressure (Pa)
\(Re\) Reynolds number
\(V\) velocity (m/s)

Greek symbols
\(\rho\) gas density (kg/m³)
\(\Delta\) difference of

Subscripts
\(\theta\) flow approaching angle (°)

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1. Introduction

Along with the temperature measurement, the flow measurement in fire experiment is one of the most basic ways to understand the fire behavior and characterize a fire environment. There are various ways such as LDV (Laser Doppler Velocimeter), PIV (Particle Image Velocimetry), hot wire anemometer, and differential pressure velocimeter, which are used to quantify the flow field [1]. In most of fire testing conditions, however, the applicable velocity measurement technique is limited due to the unsteady characteristics and the harsh environment of fire including combustion products with soot particle and large temperature variation. Therefore, traditional differential pressure velocimeter is the common in fire testing application for many reasons including convenience, robustness, suitability for large scale tests. The well-known representative for the differential pressure velocimetry is the Pitotstatic tube, however, it is sensitive to flow direction and clogging of small measuring hole due to combustion products. Therefore, the differential pressure velocimeter using robust bi-directional probe has been widely used in numerous fire testing applications such as ventilation flow measurement in compartment fires, exhaust flow measurement of large scale calorimeter, and so on. The determination of the local velocity using a bi-directional probe requires the measurement of pressure difference between the front and rear sides of the probe and the local gas density [2, 3].

\[
V = \frac{1}{k_p} \sqrt{\frac{2\Delta P}{\rho}}
\]  

(1)

where, \(k_p\) is the probe constant. Usually, the gas density is determined from the measured local temperature. For an ideal Pitot tube, the probe constant is quite close to unity, but that of bi-directional probe depends on several factors such as Reynolds number, probe shape, and orientation. McCaffrey and Heskestad [2] showed the best fit of poly-nominal curve for low Reynolds number flow (40 < Re < 3,800) with relative uncertainty of 5%. They proposed that the asymptotic value of probe constant was about 1.08 for large Reynolds number. Additionally, the measurement uncertainty of bi-directional probe can be affected by the flow approaching angle between the probe axis and the flow direction. Within 50° of flow approaching angle, the relative uncertainty of McCaffrey and Heskestad’s results is ±0.10. However, Liu et al. [4] reported that the relative uncertainty at flow angle of 30° showed the mean value of ±0.15 and maximum value of ±0.18 for low Reynolds number flow (100 < Re < 1,200).

In order to enhance reliability of the velocity measurement by bi-directional probe, the measurement uncertainty should be quantified for various flow conditions such as range of Reynolds number, flow approaching angle, temperature variation, and so on. In contrast to its extensive application in fire testing, there has been limited research to quantify the measurement uncertainty for various flow conditions and optimize the design of bi-directional probe.

The present study has been performed to examine the measurement uncertainty of bi-directional probe for flow conditions for high Reynolds number with various flow approaching angles. Besides the experimental study, a series of CFD calculations have been conducted to understand the flow characteristics near the probe associated with the flow approaching angle. It is expected that this study can contribute to enhancing the reliability of velocity measurement in fire test and can be utilized as a preliminary study for design optimization of bi-directional probe based on the understanding of detailed flow characteristics.

2. Experimental and numerical approach

The present study includes both experimental and numerical study to investigate the angular sensitivity of bi-directional probe. In the experimental study, the probe constant with Reynolds number is estimated for a standard type of bi-directional probe and compared with previous study to verify the measurement method of the present study. Then, the angular sensitivity with Reynolds number is examined within 50° of flow approaching angle. In the numerical study, a series of CFD calculations have been performed to understand the flow characteristics near the probe associated with the flow approaching angle. It is expected that this study can contribute to enhancing the reliability of velocity measurement in fire test and analyze the effect of the flow characteristics on the angular sensitivity.

2.1. Experiment

As seen in Fig. 1, experiments are conducted in a circulating wind tunnel with the test section length of 2.5 m. An axial fan was installed at the bottom of the circulating wind tunnel and flow speed inside the wind tunnel was controlled by an inverter drive. The cross section area of the test section is approximately 0.01 m², the measuring point of bi-directional probe is located at 1.5 m downstream from the entrance of test section. A bi-directional probe used in this study is a
standard type with diameter of 16 mm and L/D of 2. MKS Baratron 220D pressure transducer, which has maximum measuring pressure of 1 Torr, 0.15% of measuring error and 0.01% of resolution, was used to measure the pressure difference between front and rear side of the probe. The electrical signal from the pressure transducer was transmitted to NI cDAQ-9172 data acquisition system and the raw data was stored in personal computer through Labview program.

![Experimental setup of the circulating wind tunnel used in present study.](image)

The representative velocity was measured by a 6 mm diameter of L type Pitot static tube which has probe constant of 1.00±0.01 and 1% of measurement error for the flow approaching angle between -10° and +10°. The flow speed inside the wind tunnel is basically determined by controlling motor speed of axial fan using an inverter. Although the flow speed is proportional to the motor speed, it is influenced by the testing conditions such as ambient temperature and relative humidity. In addition to the Pitot tube, hence, a hot wire anemometer was installed at 0.5 m downstream of the entrance to monitor the reference velocity inside of the wind tunnel. Based on the relationship between the monitoring velocity using the hot wire anemometer and the measuring velocity using the Pitot tube, the representative velocity at the sampling point was determined from the monitored velocity by detailed adjusting of motor speed. The details of the tested case are listed in Table 1.

<table>
<thead>
<tr>
<th>Representative Velocity</th>
<th>Reynolds number</th>
<th>Flow approaching angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8</td>
<td>3,400</td>
<td>-45°&lt;θ&lt;45°, Δθ=5°</td>
</tr>
<tr>
<td>4.0</td>
<td>3,600</td>
<td>-45°&lt;θ&lt;45°, Δθ=5°</td>
</tr>
<tr>
<td>5.0</td>
<td>4,500</td>
<td>-45°&lt;θ&lt;45°, Δθ=15°</td>
</tr>
<tr>
<td>6.0</td>
<td>5,400</td>
<td>-45°&lt;θ&lt;45°, Δθ=5°</td>
</tr>
<tr>
<td>7.0</td>
<td>6,300</td>
<td>-45°&lt;θ&lt;45°, Δθ=15°</td>
</tr>
<tr>
<td>8.0</td>
<td>7,200</td>
<td>-45°&lt;θ&lt;45°, Δθ=5°</td>
</tr>
<tr>
<td>9.0</td>
<td>8,100</td>
<td>-45°&lt;θ&lt;45°, Δθ=15°</td>
</tr>
<tr>
<td>10.0</td>
<td>9,000</td>
<td>-45°&lt;θ&lt;45°, Δθ=5°</td>
</tr>
</tbody>
</table>

2.2. CFD Calculation

CFD (Computational Fluid Dynamics) was used to understand the detailed flow characteristics near the bi-directional probe with flow approaching angle. The flow field was calculated by using commercially available CFD package FLUENT Version 12.1 [5]. The CFD model is based on the finite volume method on a collocated grid. A non-staggered grid system was used for storage of discrete velocities and pressures. For the calculation of the 3D flow near the probe, the computational domain was divided into approximately 350,000 hexahedral cells using ICEM-CFD 4.1 package, which is a commercial CAD and mesh generation program. Fig. 2 shows the computational grid of the bi-directional probe and flow.
domain. The flow field was assumed to be isothermal of ambient temperature and the standard \(k-e\) turbulence model with wall functions was applied to solve the Reynolds stress term. The SIMPLE (Semi-Implicit Method for Pressure Linked Equation) Algorithm with under-relaxation and 2nd order upwind scheme in space was selected to solve the governing equation in their discretized form. In order to capture the detailed flow characteristics, a non-uniform grid was used to increase the grid resolution near the probe.

Fig. 2. Computational domain and the detail grid of the bi-directional probe.

3. Results and discussion

3.1. Experimental results

Figure 3 shows the measured voltage signals from the pressure transducer for given reference velocities. As seen in Fig. 3(a), the signal fluctuation for the reference velocity of 0 m/s was close to zero, the measurement error of the pressure transducer was verified by baseline fluctuation test. It is increased with the increasing reference velocity because the flow perturbation is increased for high Reynolds number. Fig. 3 (b) represents the averaged value and standard deviation of the measured signal for 5 time tests for given reference velocity. The measured voltage signal, which has a linear relationship with the pressure difference, was proportional to the square of reference velocity and the standard deviation was increased with increasing reference velocity, as mentioned above.

(a) Raw voltage signal  
(b) Velocity-voltage signal relationship

Fig. 3. Raw voltage signal measured by a pressure transducer for given reference velocity and relationship between velocity and voltage signal.

Figure 4 displays the probe constant as a function of Reynolds number at a flow approaching angle of zero. The solid line indicates the best fit of poly-nominal curve for low Reynolds number flow \((40 < \text{Re} < 3,800)\) and the dashed line means the asymptotic value of probe constant for high Reynolds number \([2]\). The present study well matched the previous research by

\[ U = \begin{cases} \text{Reference voltage} & \text{if } \text{Re} < 3,800, \\ \text{Asymptotic value} & \text{if } \text{Re} \geq 3,800. \end{cases} \]
Sette [6] for high Reynolds number. For Reynolds number till 10,000, the probe constant of both of measurement results for the high Reynolds number was higher than that of asymptotic value of 1.08.

Figure 5 shows the angular sensitivity of velocity measurement using a bi-directional probe for various flow approaching angles. The angular sensitivity of bi-directional probe is represented by the ratio of measured velocity at flow approaching angle of θ and flow approaching angle of zero.

\[
\alpha = \frac{V_\theta}{V_{\theta=0}}
\]  

(2)

In order to examine the validity of test method of present study, the angular sensitivity was compared with that of McCaffrey and Heskestad [2] for Reynolds number of 3,400. The present study showed good agreement with the result of McCaffrey and Heskestad, the maximum angular sensitivity was observed near the flow approaching angle of 30° from both results. The results measured by Liu et al. [4] showed similar trends for Reynolds number of 550, but the magnitude of angular sensitivity was larger. The maximum angular sensitivity in this study was about 1.10 for Reynolds number of 3,400, while it was approximately 1.07 in the work by McCaffrey and Heskestad.

Figure 6 compares the angular sensitivity of velocity measurement for various Reynolds numbers. Overall trend in angular sensitivity was quite similar with each tested Reynolds number. The figure shows that the angular sensitivity of bi-directional probe increased with increasing Reynolds number, but its effect decreased with increasing Reynolds number, especially for Reynolds number over 7,200. For all of tests, the maximum angular sensitivity was observed at flow
approaching angles of approximately 25–30° and the maximum value was about 1.13. This means that the relative uncertainty due to the flow approaching angle reached ±0.13 for high Reynolds number conditions in this study.

Fig. 6. Comparison of measured angular sensitivity for various Reynolds numbers.

3.2. CFD results

The present study analyzes the flow characteristics near the bi-directional probe associated with the flow approaching angle by using the computational fluid dynamics technique. Fig. 7 displays the velocity magnitude field near the bi-directional probe at the flow approaching angles of 0° and 30° for Reynolds number of 3,400, respectively. For the case of the flow approaching angle of 0°, the flow field was symmetric along the probe axis and the velocity was almost zero magnitude inside the front and rear hold of the probe. But for the flow approaching angle of 30°, the flow field was asymmetric along the probe axis and the effect of wake flow increased at the rear side of probe. This wake flow may affect the dynamics pressure variation inside of the probe hole. The angular sensitivity can be directly affected by the pressure variation inside the probe hole.

Figure 8 shows the velocity vector field near the probe at the flow approaching angles of 0° and 30° for Reynolds number of 3,400, respectively. As mentioned above, the velocity inside the probe hole for the flow approaching angle of 0° was almost zero except the entrance of the probe hole. However, there exists a circulating flow pattern inside the rear hole of probe due to the asymmetric wake flow after passing the probe body and support rods in the case of flow approaching angle of 30°. The circular flow pattern inside the probe hole is directly affected by not only the probe diameter and length of the probe but also shape of the probe itself.

Fig. 7. Calculated velocity magnitude contour near the probe with different flow approaching angles of 0° and 30° (Re=3,400).
4. Conclusions

Angular sensitivity of bi-directional velocity probe for various Reynolds numbers was studied experimentally and numerically. The experimental study investigated the effect of Reynolds number on the probe constant and angular sensitivity for high Reynolds number. The numerical study showed the detailed flow field near the bi-directional probe with the approaching angle. The conclusions are summarized as follows.

- For the parallel flow to the probe axis, the evaluated probe constant as a function of Reynolds number well matched the result of Sette [6] for high Reynolds number. It was slightly higher than 1.10 until the Reynolds number of 10,000, while the asymptotic value for high Reynolds number proposed by Heskestad and McCaffrey [2] was 1.08.
- The angular sensitivity of the present study was compared with that of McCaffrey and Heskestad for the Reynolds number of 3,400 and was well matched within overall range of flow approaching angle. The present study showed that the angular sensitivity of bi-directional probe increased with increasing Reynolds number, but its effect was decreased for Reynolds number over 7,200. The maximum angular sensitivity was observed at flow approaching angles of 25–30° and the maximum value was about 1.13.
- The CFD results showed the detailed flow field near the bi-directional probe at the flow approaching angles of 0° and 30°. The circulating flow pattern due to the asymmetrical wake flow exists inside the rear hole of the probe and the dynamics pressure may affect the angular sensitivity of velocity measurement using bi-directional probe.

In order to reduce the measurement uncertainty due to angular sensitivity of bi-directional probe, further study should be performed to optimize the design of bi-directional probe, and examine additional effects such as density variation and blockage effect [7].

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References