Measurement of airflow velocity in half-scale car model using PIV – In case of foot-mode air conditioning

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SUMMARY
Compared to architecture, automobiles are somewhat more susceptible to external thermal influences. Therefore, keeping the internal atmosphere comfortable is extremely important from the standpoint of the passengers’ health and comfort. In the present study, a half-scale car model is created by the Society of Automotive Engineers of Japan (JSAE) to clarify the airflow properties inside the car using particle image velocimetry (PIV). In the experiment, we obtain accurate data about the airflow properties, demonstrating an air stream from the air supply opening under the dashboard to the rear of the model via the driver’s foot region. Our experimental data is to be shared as a standard model to assess the environment within automobiles. The data is also for use in computational fluid dynamics (CFD) benchmark tests in the development of automobile air conditioning, which enables high accuracy prediction of the interior environment of automobiles. As a result, it should become possible to design high-quality air conditioning in automobiles.

KEYWORDS
Air conditioning, Ventilation, Standard car model, Model experiment, PIV

INTRODUCTION
Perimeter loads on automobiles are heavier than those in buildings. In addition, automobiles can hardly be provided with eaves to intercept solar radiation, or sufficient thermal insulating material and multi-layered glass for thermal insulation and air-tightness. These factors compel automobiles to control their interior environment by air conditioning. In order to ensure a comfortable interior atmosphere, it is necessary to design automotive air conditioning with care and consideration. We have to develop a highly accurate method for predicting a car’s interior environment, and then improve the air-conditioning system to ensure a comfortable environment. At present, experimentation and computational fluid dynamics (CFD) analysis are generally used to predict the atmosphere inside a car.

Concerning the atmosphere in automobiles, several studies have already been carried out. Batterman et al. (2006) proposed using tracer gas techniques to accurately measure concentrations of volatile organic compounds (VOC) in houses and vehicles, and discussed the usefulness of such techniques. Lin et al. (1992) investigated the effects of HVAC design parameters on passenger thermal comfort. The exit vent location was found to be an important factor for the flow distribution in the rear compartment. Dag et al. (2000) measured airflow velocity in a real car, namely a Volvo S80, and compared the figures with their CFD results. In this study, particle image velocimetry (PIV) was used for the velocity measurements as well as our experiments. However, turbulence intensity inside the cabin was not investigated. Kataoka and Nakamura (2001) used a three-dimensional laser flow meter to measure the
airflow distribution in a simple car model and carried out a benchmark test for CFD analysis. On the basis of the test results, the thermal sensations of the passengers were also measured. Real cars are set to be the study target in these works. Individual differences are discernible between real cars.

In the present study, we comprehensively examine the internal air environment within automobiles using a half-scale car model created with transparent acrylic resin by the Society of Automotive Engineers of Japan (JSAE). As part of that, the purpose of this report is to provide data to examine the accuracy of CFD analysis by means of a high-precision experiment using PIV. The experimental data is to be shared as a standard model to assess the atmosphere in cars and for use in CFD benchmark tests in the development of automobile air conditioning. As a result, it should become possible to accurately predict the atmosphere in vehicles using CFD analysis and design high-quality air conditioning. In our earlier paper (Ozeki et al. 2008), ventilation in vent mode was employed as the first step in the measurement of interior airflow distribution of its velocity and turbulence intensity. The next target of this study is that in foot mode.

**EXPERIMENTAL MATERIALS AND FACILITIES**

In a climate chamber as shown in Figure 1, the experiment is performed with a half-scale car model. The chamber is capable of controlling the interior temperature to an accuracy of 0.1°C. The model interior is air-conditioned with air in this chamber.

The half-scale car model as shown in Figures 2 and 3 is used in this PIV experiment. The model is symmetrical about the centerline. The model has a closable opening at the top so as to permit manipulation of the experimental devices as well as other closable openings to permit connection with ducts for interior air conditioning.
The model’s interior is air-conditioned in foot mode. Foot mode is one of the ventilation modes, supplying air from the foot region. In this experiment, four supply openings are created at the bottom of the dashboard. A rectangular duct coupled with a flexible duct is connected to each of the openings to supply air. The dimensions of the rectangular duct are 50 mm × 60 mm. Two exhaust openings are created in the rear of the model. A flexible duct is connected to each of the openings to exhaust the air. Air supply and exhaust are performed by blowers connected to the flexible ducts. The voltages applied to the blowers are controlled by constant voltage controllers to maintain the air volume at set voltage values. Air conditioning in foot mode is mainly employed for heating. The jet flows from the supply openings ascend due to positive buoyancy resulting from heating. In this experiment, a 30-mm high board is attached to the front edges of the front seats to consider the heating buoyancy and study the effects of the updraft from the foot position on the driver and passengers.

The orifice tubes used in this experiment are able to measure the airflow rate within an error margin of 1%. The airflow rate is derived from the relationship between the airflow rate and the difference in pressure before and after the throttle nozzle in this orifice tube. The differential pressure is measured using a BARATRON pressure gauge. That is also employed to measure the pressure differential inside and outside the model to confirm the ventilation accuracy.

PARTICLE IMAGE VELOCIMETRY (PIV)

The PIV system as used in the present study is designed to measure two-dimensional airflow velocity distribution. The processor calculates the instantaneous velocity by correlating two images of particles shot within a very brief interval. The images shot by a CCD camera synchronized with a pulse laser are loaded as digital data into the processor. Following is the equipment used in this PIV measurement:

- Processor: PIV 2000 Processor (Dantec Dynamics A/S, DENMARK)
- Camera: 80C40 Flow Sense (Dantec Dynamics A/S, DENMARK)

In this experiment, we measure the airflow velocity distribution in the section Y = 324.3 mm (parallel to the wall and passing through the center of the window-side supply opening near the driver’s seat) (shown in Figure 4). In order to measure the airflow velocity using PIV, tracer particles (0.25 μm ~ 60 μm in diameter), which provide ample scattered light, are sprinkled around the blower so that they are fed into the model. The pulse laser irradiates the measured section in order to shoot the images. The time interval between two images is adjusted to between 400 μs and 4,000 μs depending on the airflow velocity. We shot 300 paired images a minute and repeated the process three times to obtain 900 pairs of images. Nine hundred instantaneous velocity distributions are calculated on 900 pairs of images in the filtering condition (Adaptive Correlation as shown in Table 1). Each velocity distribution consists of 3,234 velocity data at 66 × 49 resolution.

The instantaneous velocity \( \tilde{u} \) is broken down into the mean velocity component \( U \) and the velocity variation component \( u \) as follows:

\[
\tilde{u} = U + u
\]

(1)

It is necessary to obtain the turbulent flow statistics by averaging the instantaneous velocities obtained. The mean velocity can be obtained as an arithmetic mean of the group of instantaneous velocity data as follows:
\[
U = \frac{1}{N} \sum_{k=1}^{N} \tilde{u}_k
\]  \hspace{1cm} (2)

where, \(N\) is the number of data items used in the averaging. In the present experiment, each mean velocity distribution was calculated from 900 instantaneous velocity distributions using Vector Statistics (as shown in Table 1) based on Equation 2. As shown in Figure 5, we measured 29 regions within the section to obtain extensive velocity distribution because the area covered by the CCD camera is 132.3 mm \(\times\) 178.4 mm in size.

The standard deviation (S.D.) of the instantaneous velocity relative to the mean velocity and the turbulence intensity (T.I.) can be obtained by the following equations:

\[
S.D. = \sqrt{\frac{1}{N} \sum_{k=1}^{N} (\tilde{u}_k - U)^2}
\]  \hspace{1cm} (3)

\[
T.I. = \frac{S.D.}{U} \times 100
\]  \hspace{1cm} (4)

Figure 4. Measured section.

Figure 5. Measured areas in section.

Table 1. Data processing of PIV.

<table>
<thead>
<tr>
<th>Filter</th>
<th>&lt;Interrogation Area&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive</td>
<td>● Final Interrogation area size : 32 (\times) 32</td>
</tr>
<tr>
<td>Correlation</td>
<td>● Overlap : 25% (\times) 25%</td>
</tr>
<tr>
<td></td>
<td>● Number of refinement steps : 2</td>
</tr>
<tr>
<td></td>
<td>● Number of passes/step</td>
</tr>
<tr>
<td></td>
<td>- Initial step : 2</td>
</tr>
<tr>
<td></td>
<td>- Intermediate steps : 2</td>
</tr>
<tr>
<td></td>
<td>- Final step : 2</td>
</tr>
<tr>
<td>Vector Statistics</td>
<td>● All valid vectors [including Substituted]</td>
</tr>
<tr>
<td></td>
<td>&lt;Validation&gt;</td>
</tr>
<tr>
<td></td>
<td>● Peak Validation,</td>
</tr>
<tr>
<td></td>
<td>Minimum Peak height : 1.1</td>
</tr>
<tr>
<td></td>
<td>● Local Neighborhood Validation</td>
</tr>
<tr>
<td></td>
<td>- Use Moving Average</td>
</tr>
<tr>
<td></td>
<td>- Neighborhood size : 3 (\times) 3</td>
</tr>
<tr>
<td></td>
<td>- Acceptance factor : 0.1</td>
</tr>
<tr>
<td></td>
<td>● Iterations : 1</td>
</tr>
</tbody>
</table>

EXPERIMENTAL CONDITIONS

The temperature in the climate chamber is set at 300 K because the calibration test of the orifice tubes was done for flow rates at an air temperature of 300 K. In order to set the total ventilation air volume at 100 m\(^3\)/h, the air volumes of four supply openings (SO 1 \sim 4) are set at 25 m\(^3\)/h each and those of two exhaust openings (EO 1, 2) at 50 m\(^3\)/h each (as shown in Figure 6). The humidity in the chamber is not conditioned.
RESULTS AND DISCUSSION

Ventilation accuracy
Table 2 shows the air volume at six blowers and the difference in pressure inside and outside the model measured for five minutes at 2 Hz. The mean air volume of each blower was maintained within an error of 1% against the preset air volume. The smallness of the airflow variation was confirmed; the maximum standard deviation within the six blowers was 2.3% of the mean air volume. The precision of the ventilation was also confirmed; both the sum of the supply air volumes and that of the exhaust air volumes were 100.47 m³/h. The pressure differential shows that the inner pressure was marginally higher than the outside pressure.

Table 2. Air volume and difference in pressure inside and outside the model.

<table>
<thead>
<tr>
<th>Blower no.</th>
<th>Air volume [m³/h]</th>
<th>Pressure differential [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SO 1</td>
<td>SO 2</td>
</tr>
<tr>
<td>Mean</td>
<td>25.20</td>
<td>24.99</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.49</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Mean airflow velocity
Figures 7 and 8 show the scalar map and the vector map of the two-dimensional mean airflow velocity distribution. The jet flow from SO 1 hit the board at the foot position of the seat and ascended to the ceiling with a speed decrement. The maximum airflow velocity was 2.75 m/s near the supply opening. In Zone A (as shown in Figure 10), a close-up of which is shown in Figure 9, we clearly captured that part of the jet flow went to the front of the model along the floor, which caused a small vortex due to inducement by the jet flow. In Zone B, a close-up of which is shown in Figure 9, part of the air stream hits the dashboard, which also causes a vortex between the jet flow and the driver’s seat. After reaching the ceiling with a further speed decrement, part of the air stream descended along the headrest and the backrest of the driver’s seat, creating a large circulatory flow between the dashboard and the seat (Zone C). After ascension above the rear seat, part of the air stream along the ceiling descended to the rear seat, also creating a large circulatory flow between the driver’s seat and the rear seat (Zone D).

Standard deviation and turbulence intensity
Figure 11 shows the standard deviation distribution of the airflow velocity. The time fluctuation of the airflow velocity was controlled to reduce it; the standard deviation of the jet flow from the supply opening was less than 0.3 m/s until it had traveled 100 mm. Outside of this, the standard deviation was a little higher (0.5 ~ 0.7 m/s) due to mixing with the surrounding airflow.
Figure 7. Mean airflow velocity distribution (scalar map).

Figure 8. Mean airflow velocity distribution (vector map).

Figure 9. Close-ups of vector map (Figure 7).

Figure 10. Location of Zones A to D.
Figure 11. Standard deviation of airflow velocity.

Figure 12. Turbulence intensity.

Figure 13. Instantaneous velocity around Zone C.
Figure 12 shows the turbulence intensity distribution. Near the center of the jet flow, where the standard deviation was small, the turbulence intensity was also small (less than 10%). On the outside of the jet flow, the turbulence intensity was more than 200%. In totality, the turbulence intensity was at most 100% in the area where the air stream from the supply opening to the ceiling flowed. Meanwhile, the turbulence intensity was over 200% around the center of the circulating flow such as Zones A to D (as shown in Figure 10). Figure 13 shows the vector map of the instantaneous airflow velocity in Zone C. In Zones A to D, small vortices such as shown in Figure 13 appeared and disappeared such that the turbulence intensity might have increased. As with the ventilation in vent mode, the turbulence intensity was extremely high around the driver and the rear passenger in Zones C and D. However, the airflow velocities in these areas in this foot-mode experiment were lower (0.1 ~ 0.15 m/s) than those in the vent-mode experiment. Thus, the degree of discomfort brought about by turbulence intensity in foot mode can be assumed to be smaller than in vent mode (Fanger et al. 1989).

CONCLUSIONS
In the present study, we precisely measured the airflow velocity distribution in a half-scale car model air-conditioned in foot mode using PIV. In the previous study, we obtained the airflow velocity distribution data using vent-mode ventilation which showed the jet flow from the front to the rear of the model. In this experiment, more complex and more extensive airflow properties using foot-mode ventilation were obtained. This data will be distributed as a standard model to assess the internal environment in automobiles and for use in CFD benchmark tests in the development of automotive air conditioning. It should become possible to predict automobile interior environments more accurately, which would facilitate the designing of superior air conditioning in automobiles. Future issues include measuring the Y axial airflow velocity and conducting experiments that take into account thermal effects and the human form.

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REFERENCES


