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Airflow Distribution Measurements around the Human Body Using a Thermal Manikin by Particle Image Velocimetry

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Abstract

The human body is a heat source in a room. As the human body has a complex shape, it is difficult to accurately measure the airflow distribution around the human body using a conventional anemometer. This study measured the airflow distribution around a thermal manikin acting as a human body by visualization and particle image velocimetry (PIV). The thermal manikin was 1700 mm in height, and its surface temperature was set to 30°C. The experiments were performed in the conditions when the manikin was seated on a chair. The ambient air temperature and wind velocity were experimental variables. The airflow distribution around the manikin was reported by considering the relationships between convection and ambient wind velocity. There were no differences in the airflow distribution around the manikin due to the ambient air temperature when the wind velocity in the chamber was set as 1.0 m/s. Hence, it was assumed that the ambient wind velocity was dominant in this condition. Various airflow distributions were formed around the manikin due to the difference between the body surface temperature and the ambient air temperature in the case where the wind velocity in the chamber was set to approximately equal to 0.0 m/s.

1. Introduction

Recently, computational fluid dynamics (CFD) has been used to predict the in-

door distribution of airflow, contaminants, and temperatures. The distributions greatly vary depending on the room shapes, heat source locations, window openings, and HVAC inlet and outlet ports. It is necessary to understand the thermal convection around a human body, which acts as a heat source in a room, in detail. This is necessary to predict the indoor air quality (IAQ) and thermal environment around an occupied zone in depth. Gao *et al.* calculated air flow, temperature, CO_2 concentration distribution for seated virtual thermal manikin using CFD [1]. They compared CFD results with experiment at some points. It is difficult to accurately measure the airflow distribution around the human body using a conventional anemometer because of the complex shape of the human body.

In previous studies, the focus of research reports is an airflow distribution of subregions (head, abdomen, legs, etc.) around the thermal manikin. Yousaf *et al.* (2011) simulated and measured thermal plume around human head using thermal manikin with CFD and particle image velocimetry (PIV) [2]. They measured air flow distributions around human head using two cameras of which measurement area size is about 500 × 500 mm. Cao *et al.* (2014) measured air distribution around human body in aircraft cabin using PIV [3]. This measurement was performed at 5 sub-regions of which size is 975 mm × 650 mm. Marr *et al.* (2005) measured velocimetry field in breathing zone of a thermal breathing manikin using a time-resolved PIV system [4]. This measurement area size is about 100 mm × 100 mm. However, there is very limited research on airflow distributions around the entire body of a manikin.

In this study, the airflow distributions around the entire body of a thermal manikin were measured by flow visualization and PIV. PIV is a noncontact method that simultaneously measures the airflow velocity at multiple points, and therefore PIV is preferred over conventional anemometers. However, PIV was used for relatively small areas (e.g., a square of area 500 × 500 mm). Recently, PIV can be measure airflow distributions in and around buildings for larger areas (Akabayashi *et al.*, 2013 [5]). In this study, the ambient temperature and wind velocity were experimental variables. The air flow distribution around the manikin considering relationships between convection and ambient wind velocity were reported.

2. Experimental Method

2.1. Experimental Set up

The experiment was performed in an artificial climate chamber (5000 mm width, 11,000 mm length, and 3000 mm height). The chamber could adjust the room temperature from 20°C to 35°C in increments of 0.5°C. The wind velocity in the chamber was adjusted from 0.1 m/s to 2.7 m/s. The experimental set up is illustrated in Figure 1. The thermal manikin illustrated in Figure 2 was 1700 mm in height. The surface temperature of the manikin was set to 30°C. In this paper, surface temperature of thermal manikin was homogeneous distribution. However, surface temperature of real human body has inhomogeneous distri-
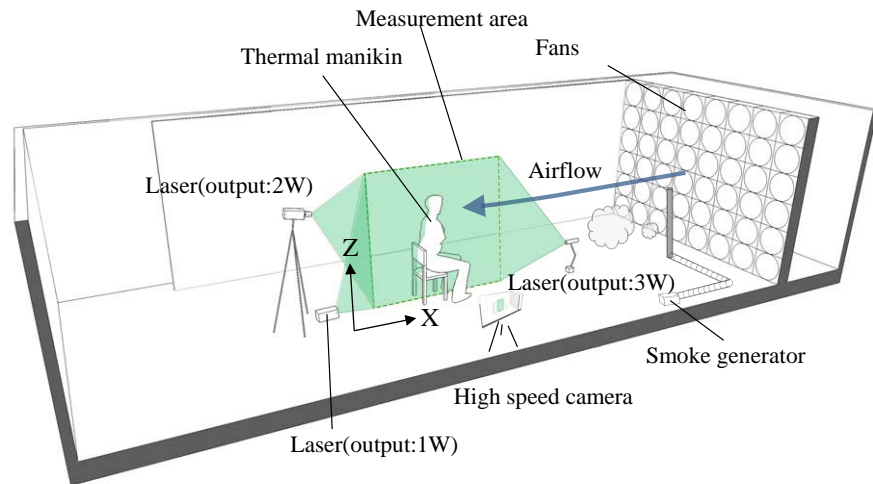
Figure 1. The experimental set up.

Figure 2. The thermal manikin.

bution. Consideration of human body surface temperature distribution is a next subject.

The experiment was performed in the condition when the manikin was seated in a chair. The manikin was dressed in a black T-shirt and tights in order to reduce the reflection of laser light sheets at its surface. In this experiment, multiple lasers irradiated the manikin in order to eliminate shadows. Three lasers with outputs of 1 W, 2 W, and 3 W were used. Three laser light sheets were adjusted on the same plane.

2.2. Experiment Cases

The experiment cases included the following. In this paper, the main experimental variable was ambient wind velocity and lower one was ambient air tem-

perature. The ambient wind velocity around the manikin was set to 1.0 m/s in case 1 or approximately equal to 0.0 m/s in case 2 (it is written as "~0.0 m/s" in the following sentences). In lower case 1, the ambient air temperature was 20°C, which was 10°C lower than the surface temperature of the manikin. In lower case 2, the ambient air temperature was 30°C, which was equal to the surface temperature of the manikin. In lower case 3, the ambient air temperature was 35°C, which was 5°C higher than the surface temperature of the manikin. All six cases were indicated in Table 1.

2.3. Experiment Equipment

Three lasers were used to perform the visualization experiment. Three laser light sheets were adjusted on the same plane. A 3 W-output laser irradiated the whole manikin from its front to visualize the entire measurement area uniformly. A 2 W and a 1 W-output laser were placed behind the manikin to irradiate it from the back. The high-speed camera used in the experiment was a Photron FASTCAM-SA3. The tracers consisted of flame-retardant smoke made by a smoke generator: DAINICHI PORTA SMOKE PS-2002. The particle size was several 10 μm or more.

2.4. Experimental and Analysis Methods

The calibration value or the conversion value between the pixel length and the real size length was 1.6935 mm/pixel as indicated in Table 2. A recognizable plate was installed and photographed at a real distance on the measurement area to calculate the calibration value. The frame rate of the high-speed camera (measurement interval) was 250 fps (4 ms) in case 1 and 60 fps (17 ms) in case 2. Each measurement took 22 s in case 1 and 45 s in case 2. The smoke generator was placed in the windward direction so that it did not influence the airflow to the maximum extent possible, and it performed seeding. The PIV analysis method was a direct cross-correlation method. We had performed sub-pixel estimation and confirmed that there was no displacement peak near integer pixel values. Uncertainty of PIV had been reported that an accuracy of 5% to 10% could be achieved for room airflow measurement using the two component PIV technique [6] [7]. Although the mean displacement of tracer was different on a

Table 1. The experimental cases.

Case		Ambient wind velocity [m/s]	Ambient air temprature [°C]	Surface temprature of the manikin [°C]
Case 1	1-1	1.0	20	30
	1-2		30	
	1-3		35	
Case 2	2-1	approximately equal to 0.0	20	
	2-2		30	
	2-3		35	

Table 2. Parameters of the PIV analysis.

Case	Case 1	Case 2
Ambient wind velocity	1.0 m/s	approximately equal to 0.0 m/s
Measurement area size	1700 mm × 1700 mm	
Image size	1024 pixel × 1024 pixel	
Calibration value	1.6935 mm/pixel	
Measurement time	22 sec	45 sec
Measurement interval	4 ms (250 fps)	17 ms (60 fps)
Interrogation region	15 pixel × 15 pixel	13 pixel × 13 pixel
Search region	±5 pixel × ±5 pixel	±5 pixel × ±5 pixel

case by case, these were about 1.1 pixels in this paper. Therefore the uncertainty of velocity measurement was estimated to be about 9% of the mean velocity. One of the purposes of this study is to organize the basic data for comparison with CFD analysis by PIV measurement. For the purpose, the subject on this paper is how to measure airflow distribution around entire real scale size human body. Therefore, we examined ways to perform a wide range of PIV measurements compared with previous studies. We are planning that the uncertainty and accuracy of the PIV measurement experiment are to be evaluated in next study (Table 3).

3. Results and Discussions

3.1. Results of PIV Analysis in Case 1

In the case of the wind velocity in the chamber set at 1.0 m/s, the airflow rose around the thermal manikin. The airflow along the chest and abdomen of the manikin was formed and moved upwards at a velocity ranging 0.1 - 0.3 m/s in each case. Vortices were formed around the back of the chair. At each ambient temperature, there were almost no differences in the airflow distribution (Figure 3).

3.2. Results of PIV Analysis in Case 2

In case 2-1, when the wind velocity in the chamber setting was ~0.0 m/s, convection occurred along the head, chest, and abdomen of the manikin. The airflow ascended at a velocity ranging 0.08 - 0.15 m/s in X = 500 - 1000 mm, and Z = 600 - 1200 mm (Figure 4).

In case 2-2, the airflow was almost stopped around the manikin in X = 600 - 800 mm, and Z = 600 - 1100 mm because there was no difference between the surface temperature of manikin and the ambient temperature. Airflow ascended slightly along the chest at a velocity ranging 0.01 - 0.03 m/s. In X = 0 - 1700 mm and Z = 1400 - 1700 mm, the airflow moved horizontally.

In case 2-3, the airflow moved downwards at a velocity ranging 0.01 - 0.08 m/s around the manikin in X = 0 - 800 mm and Z = 0 - 1700 mm, because the surface

Table 3. The experimental equipment.

Camera	High-speed camera: Photron FASTCAM-SA3 1024 pixels × 1024 pixels
Laser	DPGL-3W LD Excitation, Nd: YAG/YVO$_4$ Laser
	Wavelength: 532 nm, Output: 3 W
	Continuous light (Modulation range: 0 - 30 kHz)
	DPGL-2W LD Excitation, Nd: YAG/YVO$_4$ Laser
	Wavelength: 532 nm, Output: 2 W
	Continuous light (Modulation range: 0 - 30 kHz)
	G1000 LD Excitation, Nd: YAG/YVO$_4$ Laser
	Wavelength: 532 nm, Output: 1 W
	Continuous light (Modulation range: 0 - 30 kHz)
Software	Camera control Photron FASTCAM Viewer ver.3.3.8
	PIV analysis Flow-Expert ver1.25

(a) Case 1-1.
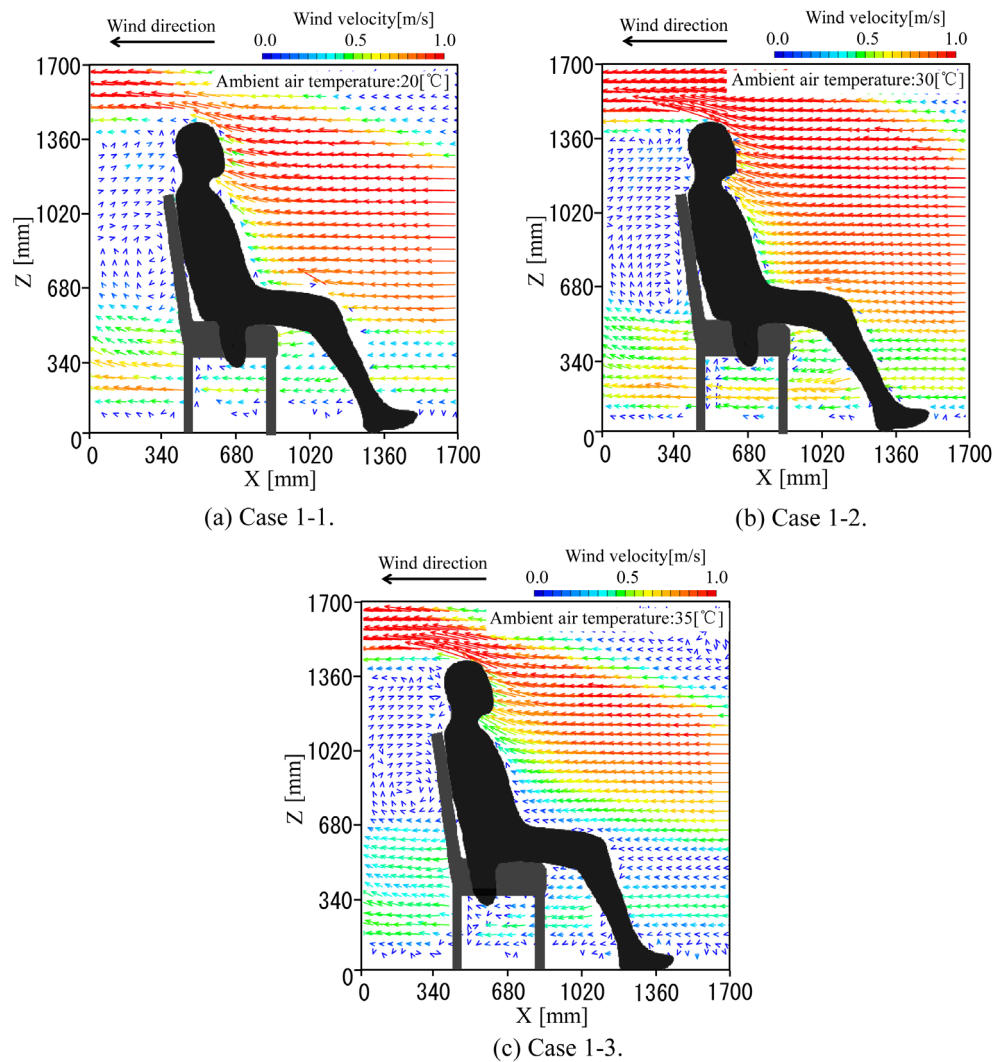
(b) Case 1-2.

(c) Case 1-3.

Figure 3. Distribution of the mean airflow velocity vector around the manikin. Ambient wind velocity is 1.0 m/s. (a) Ambient air temperature is 20°C. (b) Ambient air temperature is 30°C. (c) Ambient air temperature is 35°C.
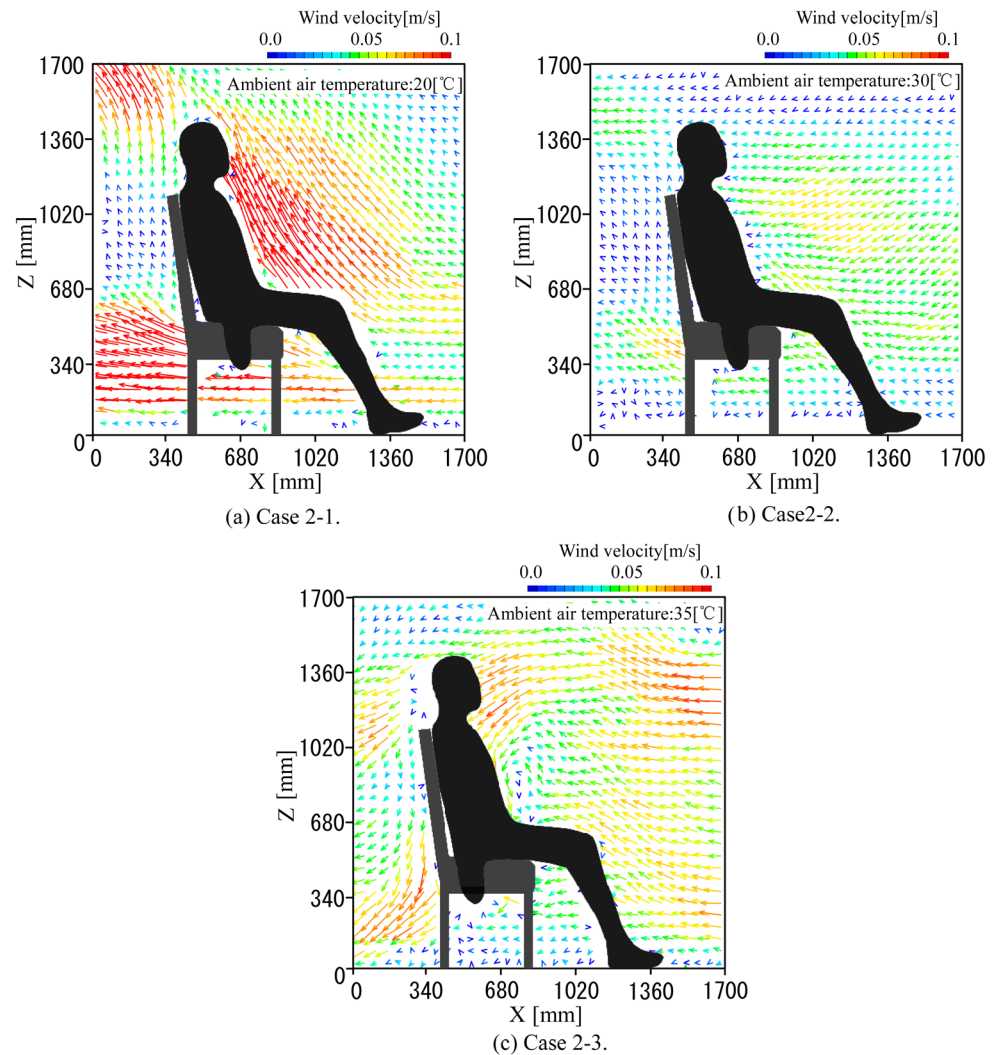
Figure 4. Distribution of the mean airflow velocity vector around the manikin. Ambient wind velocity is approximately equal to 0.0 m/s. (a) Ambient air temperature is 20˚C. (b) Ambient air temperature is 30˚C. (c) Ambient air temperature is 35˚C.

temperature of themanikin was lower than the ambient air temperature. The vortices were formed around the front of the manikin at a velocity ranging 0.01 - 0.04 m/s in X = 700 - 900 mm and Z = 700 - 1000 mm.

4. Conclusion

There was no difference in the airflow distribution when the wind velocity in the chamber was set to 1.0 m/s. Therefore, it was assumed that the ambient wind velocity was dominant in this condition. Various airflow distributions were formed around the manikin in the case when the wind velocity in the chamber was set to ~0.0 m/s. This was because of the difference between the body surface temperature and the ambient air temperature.

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