

Measurement of the convective heat transfer coefficient of the human body in the lift-up design

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Abstract. So far, the research on the convective heat transfer coefficient (h_c) in outdoor thermal comfort has mainly employed CFD simulation and wind tunnel experiments, which are difficult to fully restore the complex microclimate wind environment. In the traditional thermal comfort model, the influence of turbulence intensity (TI) on the h_c might be underestimated. This study aims to measure the h_c of the human body surface in the outdoor environment. A thermal manikin was placed in a lift-up building. The ambient wind speed ranged from 0.5m/s to 4m/s, with the TI ranging from 4% to 55%. The experimental results show that under the same wind speed, the difference in h_c between high and low TI can be up to 15%. Based on that, the regression formula for predicting h_c related to wind speed and TI was proposed. This experimental study supplements the lack of field measurement of h_c in outdoor thermal comfort research, which is helpful to improve the accuracy of the outdoor thermal comfort model.

1 Introduction

When more and more people are becoming accustomed to the convenience of shopping online and working from home, people are still encouraged to spend more time outdoors as a way of reducing the health risks associated with a lack of exercise [1]. However, as global temperature rises due to the increasing heat island effect, the heat outside is unbearable in summer, especially in areas with predominantly hot and humid climates. Therefore, outdoor thermal comfort has received much attention in recent decades.

In twenty's century, researchers pioneered the creation of thermal comfort models that quantify heat perception in terms of surrounding environmental parameters (including wind speed, air temperature, humidity, radiation), clothing insulation and metabolic rate [2]. Among them, the wind environment has been regarded as a hotspot by researchers since its complexity.

The effect of wind speed on heat transfer between the human body and the surroundings has been extensively studied. The wind tunnel experiment and validation of mathematical models are two commonly used research tools. In 1997, a study by de Dear et al. [3] conducted the wind tunnel experiments about the heat transfer coefficient (h_c) of the human body using a naked thermal manikin, and proposed regression formulas for predicting. After that, more researchers conducted similar studies, with the addition of clothing and walking as influences [4,5]. To fill the lack of data for the high wind speed in this kind of study, Li and Ito extended the experimental wind speed range to 12.67m/s in 2014 and verified the results with CFD

simulations [6]. However, in recent years, an increasing number of researchers have pointed out that turbulence intensity (TI) is also one of the important parameters affecting the h_c . The results by Yu et al [7]. in 2020 showed that ignoring TI may result in underestimating the wind effect on pedestrian thermal sensation by up to 50%. Subsequently, this underestimation effect was also confirmed by Zou et al using CFD simulations [8]. In their study, the turbulence integral length scale was added as an influencing factor and regression equations were proposed to predict h_c .

Nonetheless, there are some limitations in both wind tunnel experiments and CFD simulations. On the one hand, wind tunnels, mostly only provide constant airflow conditions with low TI. On the other hand, both methods have difficulty in reproducing the complex wind environment outdoors in reality. Therefore, the collecting of experimental data measured in the field outdoors is necessary to refine the thermal comfort model.

This study aims to explore the h_c of the human body in a realistic outdoor environment. A regression equation was proposed for predicting whole-body h_c in relation to wind speed and turbulence intensity in frontal oncoming wind conditions.

2 Methodology

2.1 The experiment site and instruments

The experiment was conducted under a lift-up design on the campus of the Hong Kong Polytechnic University, which was well shaded and well ventilated. The main

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experimental instruments included two sets of mini-weather station and a thermal manikin consisting of 20 individual segments (shown in **Fig. 1**). The mini-weather station can be used to measure environmental parameters including wind speed, wind direction, humidity, air temperature, black globe temperature, etc. The manikin was placed on a hollow metal chair to reduce the thermal conduction between them. It recorded skin temperature and heat flux every 10 seconds. 47 thermocouples were applied to the surface of manikin to double-check the accuracy of skin temperature. **Table 1.** lists the instrument models and parameters. The experiment was carried out for 5 days, approximately 5 hours per day.

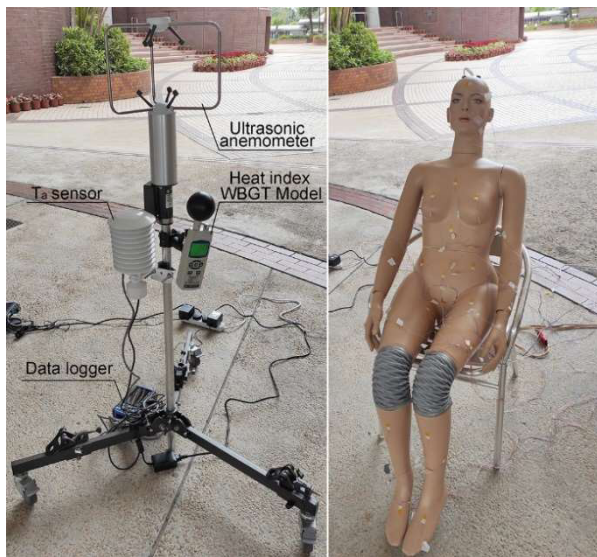


Fig. 1. The mini-weather station and the thermal manikin.

Table 1. The instrument models and parameters.

Instrument model	Resolution	Accuracy	Sampling rate
R.M. YOUNG MODEL 81000	0.01m/s	±0.05m/s	20hz
R.M. YOUNG MODEL 41382	0.01°C	±0.03°C	20hz
WBGT-2010SD	0.1°C	±0.6°C	1s
T-type thermocouple	0.1°C	±0.5°C	1s

2.2 Data processing

The aim of this study is to observe the relationship between wind speed, turbulence intensity and h_c . The turbulence intensity can be determined by this equation:

$$TI = \frac{v'}{\bar{v}} \quad (1)$$

where, v' : standard deviation of wind speed in period (m/s); \bar{v} : mean wind speed in period (m/s) (the period is 20s in this study).

The heat exchange between the thermal manikin and the surroundings consists of two parts: convection and radiation:

$$Q = R + C = h_r(t_s - t_m) + h_c(t_s - t_a) \quad (2)$$

where, h_r : radiative heat transfer coefficient ($W/m^2/K$); h_c : convective heat transfer coefficient ($W/m^2/K$); t_s : manikin's skin temperature ($^{\circ}C$); t_m : mean radiant temperature ($^{\circ}C$); t_a : air temperature ($^{\circ}C$).

h_c can be calculated by using the mean radiant temperature:

$$R = \sigma \epsilon f_e (t_s^4 - t_m^4) \quad (3)$$

where, σ : Stefan-Boltzmann constant= 5.67×10^{-8} ($W/m^2/K^4$); f_e : the effective radiation area factor. The values of f_e refer to the experimental results of Oguro et al. [9].

The calculation of t_m requires the measurement of black globe temperature:

$$t_m = [(t_b + 273)^4 + \frac{1.1 \times 10^8 v^{0.6}}{\epsilon D^{0.4}} (t_b - t_a)]^{1/4} - 273 \quad (4)$$

where, t_b : black globe temperature ($^{\circ}C$); ϵ : emissivity=0.095; D : globe diameter=0.075m

3 Results and Discussion

3.1 The effect of wind speed and turbulence intensity on convective heat transfer coefficient

The experimentally measured wind speed ranged from 0.5m/s to 4m/s. The corresponding turbulence intensities were plotted in **Fig. 2**. It can be seen that the TI was roughly negatively correlated with the wind speed. The h_c calculated for the different TI were plotted in **Fig. 3**. The values of high, medium and low TI were derived from the upper quartile, median and low quartile of the box plot at different wind speeds respectively.

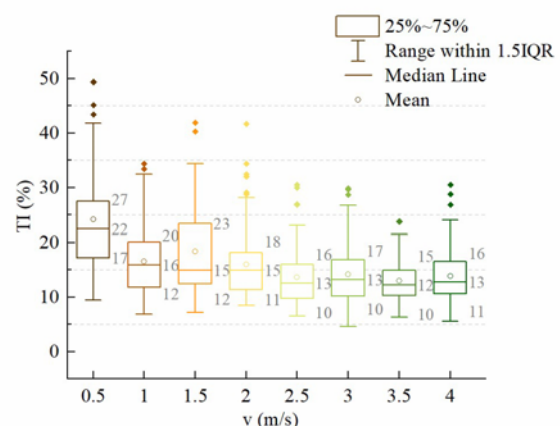


Fig. 2. The TI distribution at different wind speeds.

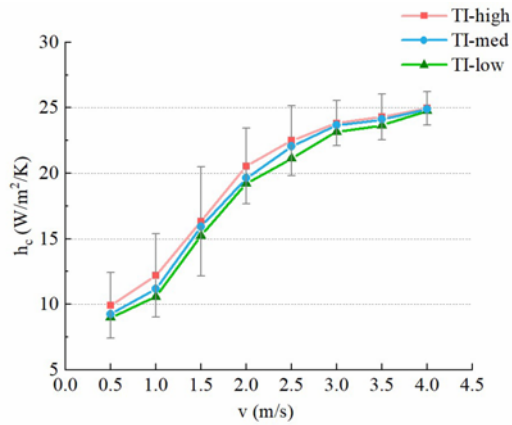


Fig. 3. h_c on manikin surface at different wind speeds and TI.

The whole body h_c increases exponentially as a function of wind speed from 9 W/m²/K to 25 W/m²/K. Error bars indicate the standard deviation of h_c at that wind speed. The effect of TI on h_c can be observed. At the same wind speed, h_c was positively correlated with TI. Based on the experimental results, not considering TI would lead to deviations in the true h_c . The observed results are similar to those of Yu et al. [7] and Zou et al. [8]. In the range of TI measured in this experiments, the difference in h_c between high and low TI groups can be up to 15% at the same wind speed.

3.2 Regression equation for convective heat transfer coefficient

In order to clarify the effect of TI on h_c , this study proposed a regression equation with wind speed and TI as dependent variables. Grisablerti and Kondjoyan carried out experiments in 1999 on the factors affecting the transfer coefficient of cylinders [10]. They found that compared with the shape characteristics, the fluid properties had a greater influence on the transfer coefficient, including wind speed and turbulence intensity. They also proposed the following formula:

$$h = Av^n * (1 + BTI * v^{0.5}) \quad (5)$$

where A, B, n are parameters. Since most segments of the human body are similar to cylinders. Yu et al. [7] have proposed the relationship based on this for predicting h_c of human body. In this study, this equation

(5) was used to fit the relationship between v, TI and the whole-body h_c (shown in Fig. 4). The R² value of this regression formula is 0.81. The following equation was fitted by the least-squares method:

$$h_c = 12.52v^{0.5} * (1 + 0.23TI * v^{0.5}) \quad (6)$$

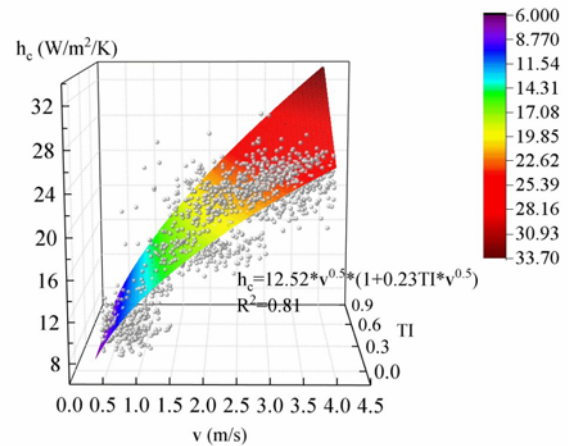


Fig. 4. Regression equation for the whole-body h_c .

3.3 Comparison of different period when calculating TI

1-min is the period commonly used in studies of thermal comfort and turbulence intensity [11,12]. However, there is often gust wind outdoors which is usually less than 20s [13]. Fig. 5 shows the different results of h_c fitted by TI using periods 20s and 1-min respectively. In comparison, the h_c using period 20s was slightly larger than using 1-min. As pointed out by Yu et al. [14], averaging period 1-min for calculation may attenuate the effect of gust wind on h_c . The period 20s used in this study was more focused on capturing the effect of the gust wind on h_c .

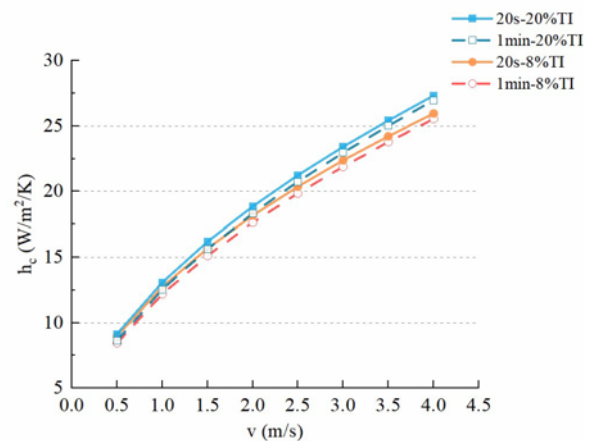


Fig. 5. The comparison of h_c fitted using period 20s and 1-min respectively.

3.4 Comparison of experimental results with other studies

Fig. 6. displays the predicted whole-body h_c of this study compared with the results of other researchers. For comparison purposes, TI for the present study was set to 8% to plot the curve, which focused on the frontal incoming wind. It can be observed that the h_c of the present prediction is higher than the experimental results of de Dear et al. [3] at the reported TI between 4%-8%, averaging about 19% higher. At the same TI of 8%, the result of the present study was lower than the prediction

of Zou et al. [8], with a maximum difference of 23% in the wind range of 4m/s. Meanwhile, the result at high wind speeds is similar to those of Yu et al [7], while differing in the lower wind speed range, up to 24% difference at 0.5m/s. The reason for the discrepancy in the low wind speed may be due to the higher TI in this section collected in this study compared to other studies, which may lead to a relative overestimation of $h_{c\infty}$.

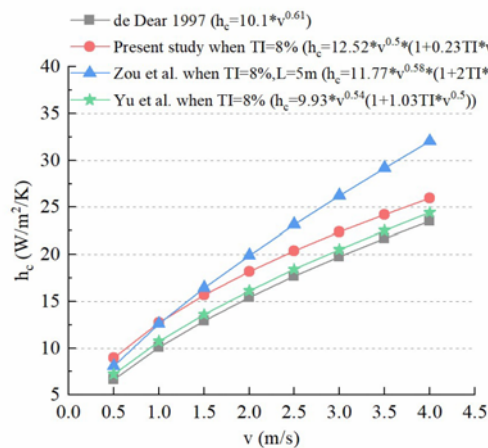


Fig. 6. The comparison of the result in this experiment with other studies.

4 Conclusion

In this study, the h_c for human surfaces were measured outside. A regression formula was developed based on the experiments to predict h_c in relation to wind speed and turbulence intensity in frontal wind conditions. The experimental results confirm that wind turbulence intensity significantly affects the whole-body h_c . The difference in h_c between high and low TI groups can be up to 15% at the same wind speed. The present study remedies the limitation of the inadequate coverage of wind turbulence intensity in previous related wind tunnel studies and expands the data for measuring h_c of human surfaces in the real outdoor environment. It could be a reference for further refinement of outdoor thermal comfort models.

This experiment is for frontal wind conditions. Future research will include the effects of different wind directions and propose regression formulas for predicting h_c in each segment of the human body.

This research was supported by the Ph.D. studentship funded by The Hong Kong Polytechnic University. The author would like to thank Mr. Kenny Huang, Mr Billy Yan, and Dr Hui Tang for their help with the calibration of the ultrasonic anemometers.

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