Wind Engineering Joint Usage/Research Center
FY2025 Research Result Report

Research Field: Indoor environment
Research Year: FY2025
Research Number: 252008
Research Theme: Effect of wind speed and turbulence intensity on summer clothing insulation: A wind tunnel study

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Budget [FY2025]: 300,000 Yen

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1. Research Aim

This study aims to achieve two research objectives. First, to investigate the effect of clothing fit on the clothing insulation of summer clothing under windy conditions. Second, to examine the influence of turbulence intensity on clothing insulation. Wind tunnel experiments were conducted to obtain experimental data on clothing insulation under different levels of clothing fit, wind speed and turbulence intensity. The findings will provide a scientific basis for the accurate prediction of human thermal comfort as well as rational clothing selection for human bodies in indoor and outdoor environments.

2. Research Method

The experiment was conducted in a multi-fan wind tunnel, as shown in Figure 1. The air flow in the wind tunnel was created by a "fan wall" composed of 48 small fans, which can simulate a uniform or turbulent wind environment by adjusting rotational speed of each small fan. Wind speed was measured by six hot wires. These hot wires were placed at 0.35 m, 0.8 m, 1 m, 1.3 m, 1.5 m, and 1.7 m above the floor. Air temperature was measured at two heights: 1.1 m and 1.9 m.

Figure 1. Multi-fan wind tunnel.

We used a nude 20-zone Newton thermal manikin (Measurement Technology Northwest, USA) to measure the thermal resistance of the boundary air layer, as detailed in Figure 2(a) and Table 1. The boundary air layer is between the skin and external environment, shown in Figure 2(b). Additionally, the thermal manikin was in three postures: front-facing the wind, back-facing the wind and left-side-facing the wind.

The thermal resistance of boundary air layer (R_{BAL}) can be calculated using formula (1) to (5) [1]:

$$Q_r = h_r \cdot (T_{sk} - T_r) \quad (1)$$

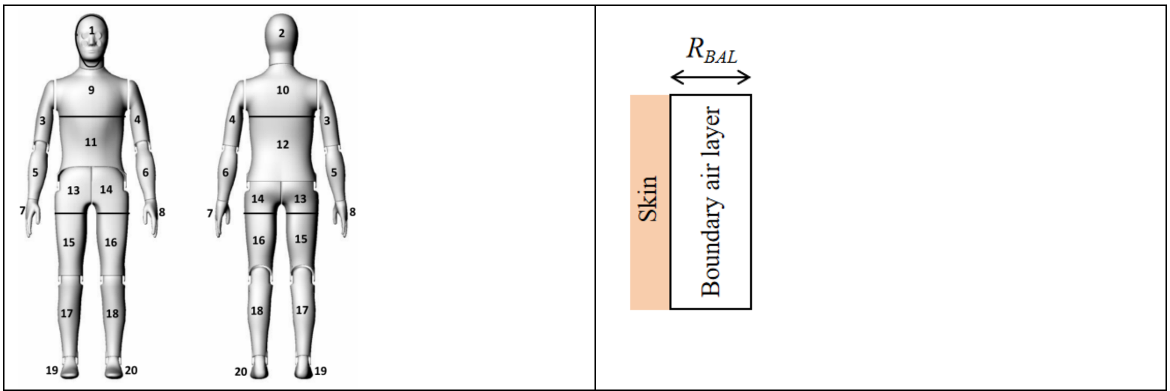
$$Q_c = Q - Q_r \quad (2)$$

$$h_c = Q_c / (T_{sk} - T_a) \quad (3)$$

$$h = h_c + h_r \quad (4)$$

$$R_{BAL} = 1/h \quad (5)$$

where Q_r is the radiant heat loss, W/m²; Q_c is the convective heat loss, W/m²; Q is the total heat loss, W/m²; h_r is the radiant heat transfer coefficient, listed in Table 1, W/m²/K; h_c is the convective heat transfer coefficient, W/m²/K; h is the total heat transfer coefficient, W/m²/K; T_a is the air temperature, 22°C; T_{sk} is the skin temperature, 34°C; T_r is the radiant temperature, assumed to be the same as air temperature, K; R_{BAL} is the thermal resistance of boundary air layer, m²·K/W.



(a) (b)

Figure 2. Unclothed thermal manikin: a) body segments marked by numbers, b) thermal resistance of boundary air layer (R_{BAL}).

Table 1. Surface area, height above the floor, and radiative heat transfer coefficient (h_r) across unclothed body segments [2].

Number	Body segment	Surface are (m²)	Height above the floor (m)	h_r (W/m²K)
1	Face	0.0475	1.6	4.21
2	Head	0.0972	1.6	2.86
3	R. Upper Arm	0.0687	1.2	3.42
4	L. Upper Arm	0.0687	1.2	3.42
5	R. Forearm	0.0606	1.0	3.57
6	L. Forearm	0.0606	1.0	3.72
7	L. Hand	0.046	0.8	4.10
8	R. Hand	0.046	0.8	4.10
9	Chest	0.121	1.3	2.86
10	Shoulders	0.1009	1.3	2.93
11	Stomach	0.1192	1.1	3.07
12	Back	0.094	1.1	3.20
13	R. Hip	0.0815	0.9	2.74
14	L. Hip	0.0815	0.9	2.48
15	R. Thigh	0.1269	0.7	4.11
16	L. Thigh	0.1269	0.7	3.89
17	R. Calf	0.1213	0.3	4.35
18	L. Calf	0.1213	0.3	4.70
19	R. Foot	0.0597	0.05	7.14
20	L. Foot	0.0597	0.05	6.36

In this part of the experiment, the manikin was dressed in a T-shirt and shorts. The manikin was in three postures: front-facing the wind, back-facing the wind and left-side-facing the wind. Both T-shirt and shorts included S size and XL size, as shown in Figure 3(a) and 3(b). The basic measurement of clothing is detailed in Table 2 and Table 3. The total thermal resistance includes clothing thermal resistance and boundary air layer thermal resistance, as shown in Figure 3(c). In addition, it is assumed that the boundary air layer thermal resistance on the clothing outer surface is consistent with that measured by the nude manikin.

The intrinsic clothing insulation (I_{CL}) and total insulation (I_T) can be calculated using formula (6) to (9) [1]:

$$R_T = (T_{sk} - T_a) / Q \tag{6}$$

$$R_{CL} = R_T - R_{BAL} / f_{cl} \tag{7}$$

$$I_{CL} = R_{CL} / 0.155 \tag{8}$$

$$I_T = R_T / 0.155 \tag{9}$$

where R_T is the total thermal resistance from skin to external environment, m^{2}K/W; R_{CL} is the clothing thermal resistance, m^{2}K/W; f_{cl} is the clothing area factor, with 1.27 for S-size clothing and 1.32 for XL-size clothing, estimated by the empirical formula [3]; I_{cl} is the intrinsic clothing insulation, clo; I_T is the total insulation, clo.

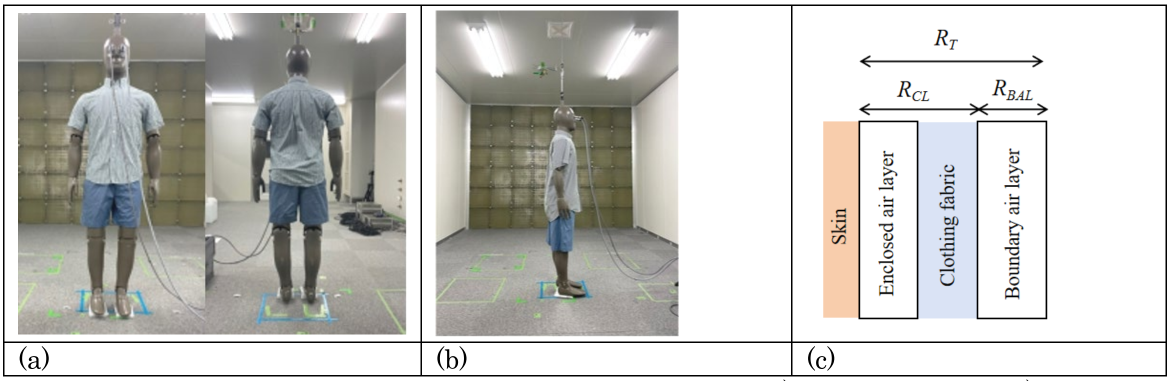


Figure 3. Clothed thermal manikin in T-shirt and shorts: a) S-size garment, b) XL-size garment, (c) total thermal resistance (R_T) and clothing thermal resistance (R_{CL}).

Table 2. Basic measurement of T-shirt.

Size	Bust (cm)	Neck line (cm)	Cuff around (cm)	Bottom around (cm)	T-shirt length (cm)	Sleeve length (cm)
S	96	35	38	96	70	22.5
XL	116	42	44	116	80	24

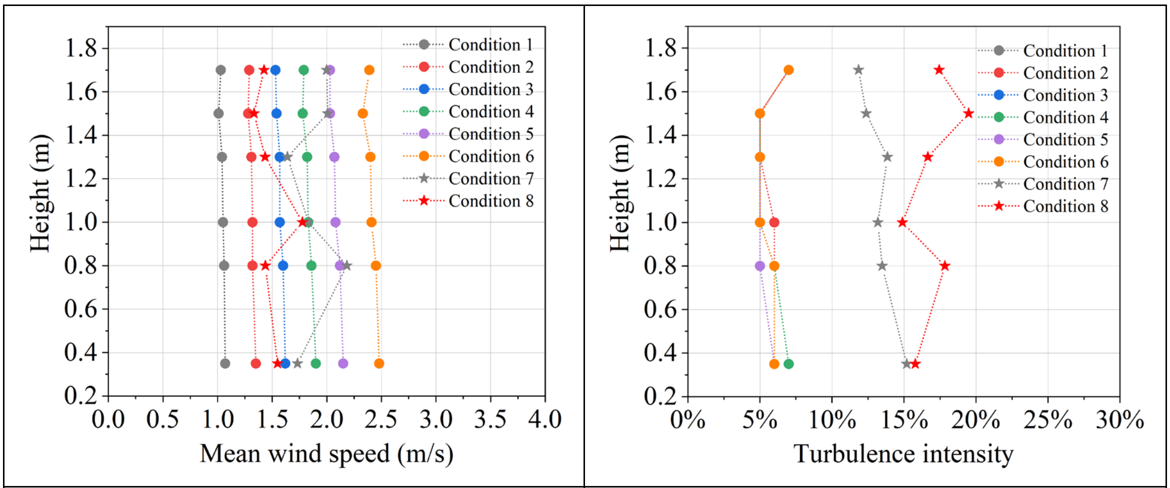
Table 3. Basic measurement of shorts.

Size	Waist (cm)	Cuff around (cm)	Shorts length (cm)
S	71	54	49
XL	88	60	53.5

3. Research Result

3.1 Wind Profiles

A total of eight wind conditions were tested in this study, including six uniform wind conditions and two turbulent wind conditions. Figure 4(a) shows the mean wind speed of each condition. For the six uniform wind conditions (Conditions 1–6), the mean wind speed increases gradually from 1.0 m/s to 2.4 m/s. For the two turbulent wind conditions, the mean wind speeds are 1.85 m/s for Condition 7 and 1.6 m/s for Condition 8, respectively. Figure 4(b) shows the corresponding turbulence intensity. The turbulence intensity of the six uniform wind conditions is maintained at approximately 6%. In contrast, the turbulence intensity is about 14% for Condition 7 and 16% for Condition 8.



(a) (b)

Figure 4. Wind conditions: a) mean wind speed, b) turbulence intensity.

3.2 Effect of clothing fit on clothing insulation in uniform wind conditions

Figure 5 shows the clothing insulation at the position of chest. When front-facing and side-facing the wind, the clothing insulation of the XL size clothing is significantly lower than that of the S size; among them, the clothing insulation of the XL size clothing shows an upward trend as the wind speed increases, while that of the S size clothing remains almost unchanged with the increasing wind speed. When back-facing the wind, the clothing insulation of the S size and XL size clothing is close to each other, and is almost unchanged with the increase of wind speed.

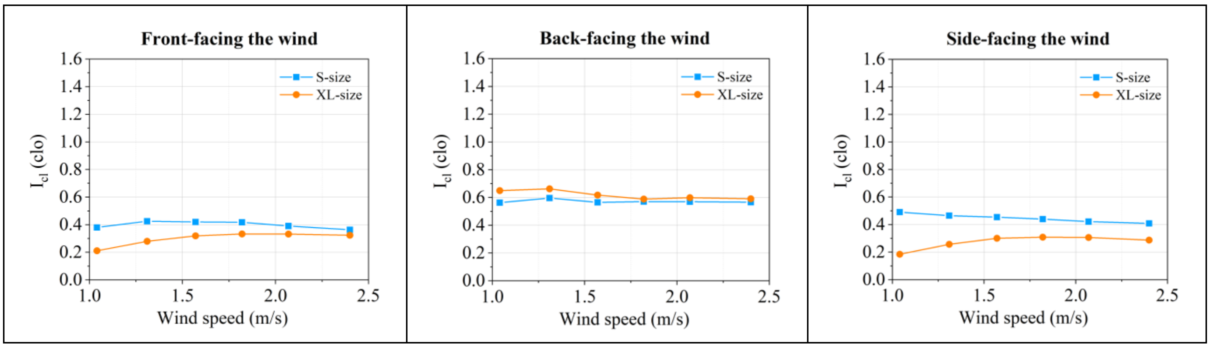


Figure 5. Clothing insulation at the position of chest in uniform wind conditions.

Figure 6 presents the clothing insulation at the position of stomach. When front-facing and side-facing the wind, the clothing insulation of the XL size clothing is significantly lower than that of the S size. Among them, the clothing insulation of the S size clothing shows a downward trend with the increase of wind speed in both postures; the XL size clothing exhibits differential characteristics — when front-facing the wind, its clothing insulation increases with the rise of wind speed, while when side-facing the wind, it first rises to an extreme point and then decreases gradually. When back-facing the wind, the clothing insulation of the S size and XL size clothing are very close, and both show a downward trend with the increase of wind speed.

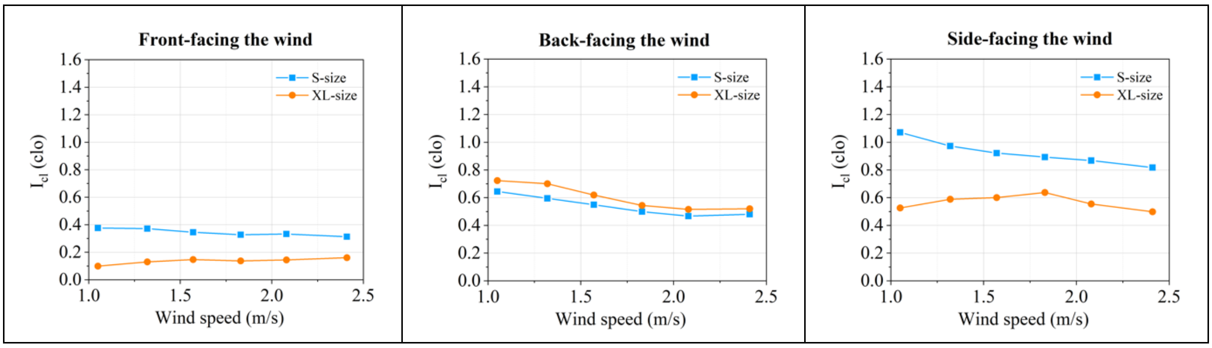


Figure 6. Clothing insulation at the position of stomach in uniform wind conditions.

Figure 7 illustrates the clothing insulation at the position of back. When front-facing and side-facing the wind, the clothing insulation of the XL size clothing is significantly lower than that of the S size. When front-facing the wind, the clothing insulation of both the S size and XL size clothing first increase with the rise of wind speed and then gradually tend to stabilize. When side-facing the wind, the clothing insulation of the S size clothing shows a continuous decreasing trend, while that of the XL size clothing first rises to an extreme point and then decreases gradually. When back-facing the wind, the clothing insulation of the XL size clothing is lower than that of the S size when the wind speed is less than 2 m/s; as the wind speed further increases, the clothing insulation of the two tend to be close, and both show a decreasing trend with the increase of wind speed.

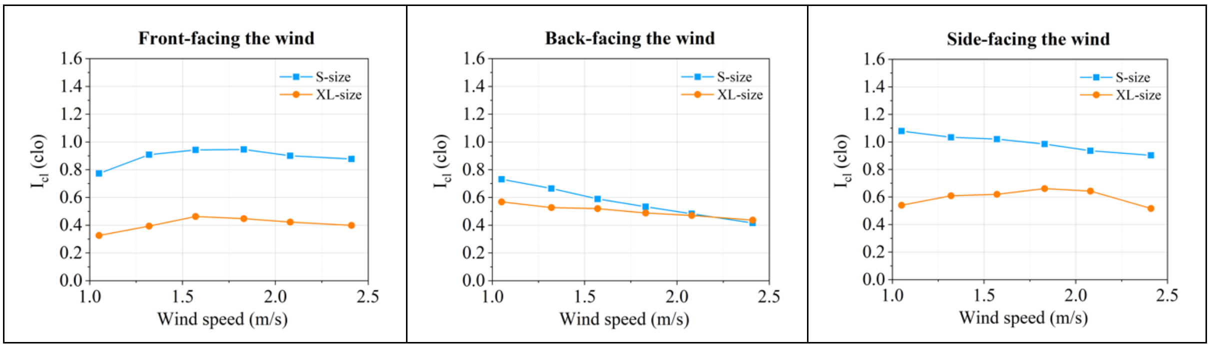


Figure 7. Clothing insulation at the position of back in uniform wind conditions.

Figure 8 shows the clothing insulation at the position of shoulders. When front-facing, back-facing, and side-facing the wind, the clothing insulation of the XL size clothing is always lower than that of the S size. Only when front-facing the wind and the wind speed exceeds 2 m/s, the clothing insulation of the two sizes becomes very close. For the variation trend, when front-facing the wind, the clothing insulation of both sizes increases with the rise of wind speed; when back-facing the wind, their clothing insulation decreases as the wind speed increases; when side-facing the wind, the clothing insulation of the S size clothing gradually increases with increasing wind speed, while that of the XL size clothing first rises to an extreme point and then decreases.

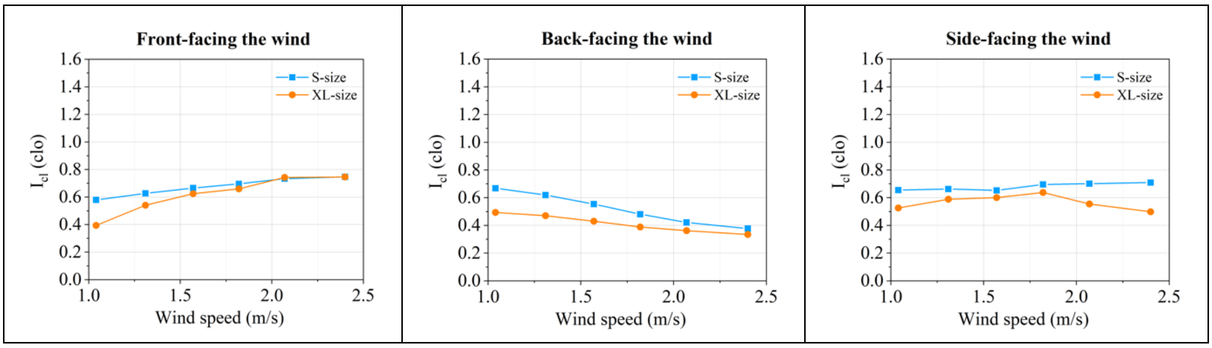


Figure 8. Clothing insulation at the position of shoulders in uniform wind conditions.

Figure 9 presents the clothing insulation at the position of hips. When front-facing the wind, the clothing insulation of the XL size clothing is significantly lower than that of the S size, and both shows a trend of first increasing and then decreasing with the rise of wind speed. When back-facing the wind, the clothing insulation of the S size clothing is obviously lower than that of the XL size; the clothing insulation of the S size clothing shows a significant downward trend as wind speed increases, while that of the XL size remains basically stable. In the condition of side-facing the wind, the clothing insulation of the XL size is initially lower than that of the S size, but when the wind speed exceeds approximately 1.6 m/s, the clothing insulation of the XL size surpasses that of the S size.

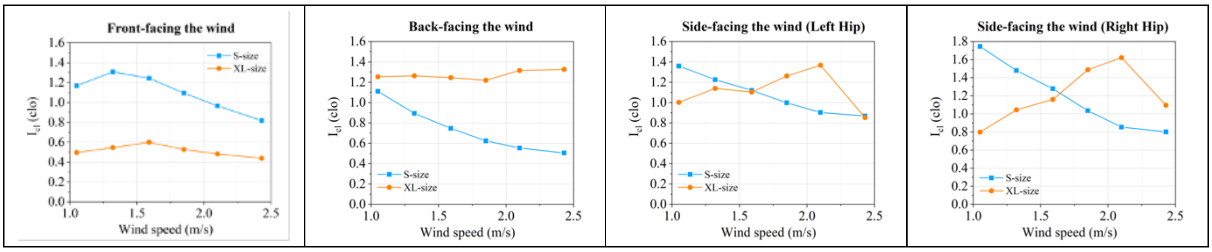


Figure 9. Clothing insulation at the position of hips in uniform wind conditions.

Figure 10 illustrates the clothing insulation at the position of thighs. Overall, the clothing insulation of the S size clothing is significantly lower than that of the XL size. The only exception is the side-facing wind posture with a wind speed below 1.25 m/s, where the clothing insulation of the XL size clothing at the right thigh is slightly lower than that of the S size. For the variation trend, in the three postures (front-facing, back-facing, and side-facing the wind), the clothing insulation of the S size clothing constantly decreases as wind speed increases. In contrast, the clothing insulation of the XL size clothing exhibits differentiated characteristics — when front-facing the wind, it first rises and then decreases; when back-facing the wind, it remains stable initially and then shows an upward trend; when side-facing the wind, it presents a distinct upward trend.

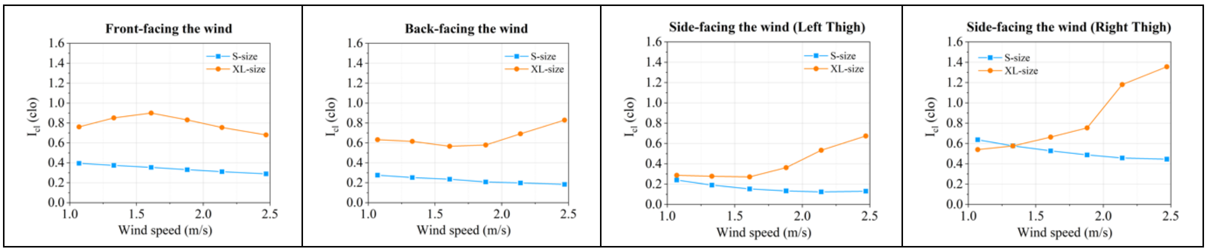


Figure 10. Clothing insulation at position of thighs in uniform wind conditions.

Figure 11 presents the clothing insulation at the position of upper arms. In the three conditions of front-facing, back-facing, and side-facing the wind, the clothing insulation of the S size clothing is lower than that of the XL size. The only exception is that when side-facing the wind, the clothing insulation of the S size and XL size clothing at the left upper arm is basically equal. Regarding the variation trend, regardless of the wind direction, the clothing insulation of the S size clothing shows a continuous downward trend as the wind speed increases. In contrast, the clothing insulation of the XL size clothing exhibits differentiated characteristics — for both upper arms when front-facing the wind and the right upper arm when side-facing the wind, the clothing insulation first increases and then slightly decreases with the rise of wind speed; for both upper arms when back-facing the wind and the left upper arm when side-facing the wind, the clothing insulation shows a downward trend as the wind speed increases.

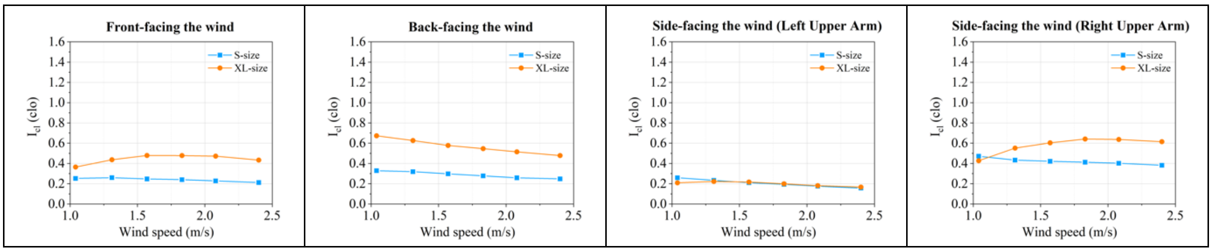


Figure 11. Clothing insulation at the position of upper arms in uniform wind conditions.

Figure 12 shows the clothing insulation for whole clothed body parts. For front-facing posture, when the wind speed is lower than 1.6 m/s, the clothing insulation of our XL-size clothing is lower than that of our S-size clothing; when the wind speed exceeds 1.6 m/s, the two are basically equal. When back-facing the wind, the clothing insulation of S-size clothing is significantly lower than that of XL-size clothing. When side-facing the wind, when the wind speed is below 1.8 m/s, the clothing insulation of XL-size clothing is obviously lower than that of S-size clothing; however, when the wind speed exceeds 1.8 m/s, the clothing insulation of XL-size clothing surpasses that of S-size clothing.

In terms of variation trends in our study, the clothing insulation of S-size clothing continuously decreases with increasing wind speed regardless of the wind direction. In contrast, the clothing insulation of XL-size clothing shows more complex trends: it first increases and then decreases when front-facing and side-facing the wind, while first decreases and then increases when back-facing the wind. In previous relevant studies, Gao et al. [4] used autumn thick clothing, while Oguro et al. [5] used long-sleeved shirts and trousers with all openings closed. Both studies found that clothing insulation continuously decreases as wind speed increases, which is consistent with the variation trend of S-size clothing, but different form the trend of XL-size clothing in this study.

This difference may be attributed to the characteristics of loose-fitting clothing: when the clothing sways in the wind, the air gap between XL-size clothing and the skin has a larger swing space, leading to dynamic changes in the air gap thickness [6]. Existing studies have found that there is a non-linear relationship between clothing insulation and air gap thickness, generally showing a "first increase and then decrease" pattern [7-9]. In the initial stage, an increase in air gap thickness can reduce clothing insulation; however, when the thickness exceeds a critical value, the convective heat transfer inside will be enhanced, resulting in a decrease in clothing insulation. In addition, the swing amplitude and fitting state of XL-size clothing vary under different wind directions: static air layers may form in areas where the clothing fits closely to the skin, and hinder the inner airflow, thus increasing local thermal resistance [10]. Meanwhile, dynamic air gaps in non-fitting areas may reduce thermal resistance due to intensified convective heat transfer [10]. These factors make the thermal resistance of loose-fitting clothing exhibit a distinct variation trend compared to tight-fitting clothing (which has a thin and stable air gap, with thermal resistance only affected by wind speed-dominated convective heat transfer).

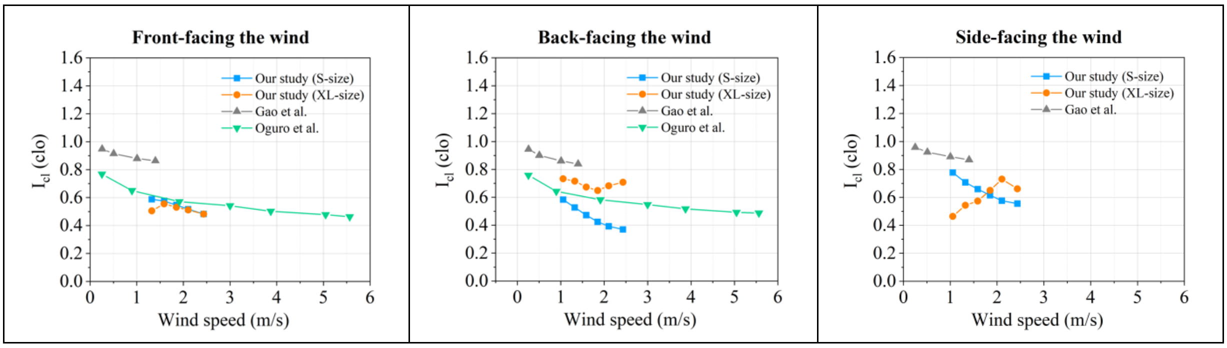


Figure 12. Compare clothing insulation of whole clothed body with other studies in uniform wind conditions.

3.3 Effect of turbulence intensity on clothing insulation

For S-size clothing, the effect of turbulence intensity on clothing insulation was not significant. Clothing insulation only fluctuated slightly and could either increase or decrease. In contrast, for XL-size clothing, turbulence significantly increased clothing insulation regardless of the wind direction.

Previous studies have shown that turbulence significantly enhances convective heat transfer on the skin surface of nude bodies, thereby reducing surface thermal resistance [11]. However, for clothed bodies, the effect of turbulence on clothing insulation is more complex, which can be explained by three mechanisms [12]. First, turbulence induces clothing movement and changes the thickness and structure of the air gap between the clothing and the skin surface. Second, turbulence strengthens the disturbance and convective heat transfer inside the air gap, which tends to reduce clothing insulation. Third, turbulence disturbs the original airflow direction within the air gap and weakens air circulation and heat exchange, thereby increasing clothing insulation.

For loose-fitting XL-size clothing, the clothing is more prone to deformation and the air gap is larger. In this case, the effect of turbulence in disturbing airflow direction and reducing air exchange dominates, so turbulence overall significantly increases clothing insulation.

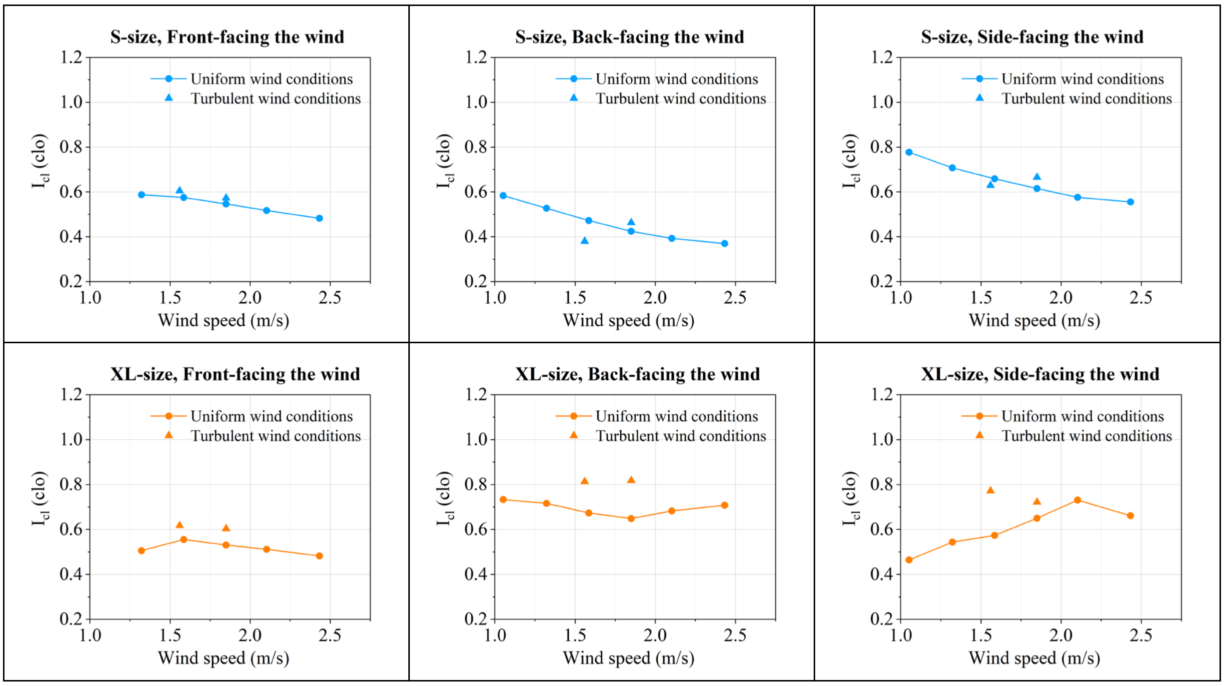


Figure 13. Effect of turbulence intensity on clothing insulation of whole clothed body.

3.4 Conclusions

This study investigates the clothing insulation characteristics of tight-fitting (S-size) and loose-fitting (XL-size) clothing under different wind speeds, wind directions, and turbulence intensities. The key findings are as follows:

1. For tight-fitting S-size clothing, the clothing insulation of whole clothed body decreases continuously with increasing wind speed, independent of wind direction.

2. For loose-fitting XL-size clothing, as the wind speed increases, the clothing insulation of whole clothed body shows wind-direction dependence. It first increases and then decreases under front and side wind, while it first decreases and then increases under back wind.

3. For local body parts, XL-size clothing shows lower clothing insulation than S-size on the torso, whereas the opposite is found on the thighs and upper arms. Clothing insulation of hips varies with wind direction and speed.

4. The effect of turbulence intensity on clothing insulation is related to clothing size. Increased turbulence intensity has no significant influence on S-size clothing insulation, but significantly increases clothing insulation for XL-size clothing under all wind directions, mainly because turbulence changes the structure of the air gap and disturbs the airflow direction inside the air gap.

This study supplements clothing insulation data for different clothing sizes under various wind speeds, wind directions, and turbulence intensities. The results can provide references for selecting suitable clothing to improve human thermal comfort.

Reference

[1] H. Zhang, X. Wan, R. Zheng, et al., A new model for evaluating dynamic clothing thermal comfort, International Journal of Thermal Sciences. 215 (2025) 109946-109946.
[2] M. Fojtlín, J. Fišer, M. Jícha, Determination of convective and radiative heat transfer coefficients using 34-zones thermal manikin: Uncertainty and reproducibility evaluation, Experimental Thermal and Fluid Science. 77 (2016) 257-264.
[3] J. Smallcombe, S. Hodder, D. Loveday, et al., Updated database of clothing thermal insulation and vapor permeability values of western ensembles for use in ASHRAE Standard 55, ISO 7730, and ISO 9920, ASHRAE Transactions. 127 (2021) 773-799.
[4] S. Gao, R. Ooka, W. Oh, Experimental investigation of the effect of clothing insulation on thermal comfort indices, Building and Environment. 187 (2021) 107393.
[5] M. Oguro, E. Arens, R. de Dear, et al., Convective heat transfer coefficients and clothing insulations for parts of the clothed human body under airflow conditions, Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ). 67 (2002) 21-29.
[6] Y. Shao, C. C. Loy, B. Dai, Towards multi-layered 3D garments animation, Proceedings of the IEEE/CVF International Conference on Computer Vision (ICCV), 2023, 14361-14370.
[7] Y.S. Chen, J. Fan, X. Qian, et al., Effect of Garment Fit on Thermal Insulation and Evaporative Resistance, Textile Research Journal. 74 (2004) 742-748.
[8] J. Li, Z. Zhang, Y. Wang, The relationship between air gap sizes and clothing heat transfer performance, Journal of the Textile Institute. 104 (2013) 1327-1336.
[9] Y. Lee, K. Hong, S.-A. Hong, 3D quantification of microclimate volume in layered clothing for the prediction of clothing insulation, Applied Ergonomics. 38 (2007) 349–355.
[10] C.A. Wilson, R.M. Laing, D.J. Carr, et al., Air and air spaces—the invisible addition to thermal resistance, Journal of the Human-Environment System. 5 (2002) 69-77.
[11] Y. Yu, J. Liu, K. Chauhan, R. de Dear, J. Niu, Experimental study on convective heat transfer coefficients for the human body exposed to turbulent wind conditions, Building

and Environment. 169 (2020) 106533.
[12] P.M. Ligrani, N.K. Burgess, Se Youl Won, Nusselt Numbers and Flow Structure on and Above a Shallow Dimpled Surface Within a Channel Including Effects of Inlet Turbulence Intensity Level, Journal of Turbomachinery. 127 (2004) 321–330.

4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]

[Published papers]

1. Effects of wind-induced deformation on the total thermal resistance of clothing - A case study with T-shirt (under review)
2.

[Presentations at academic societies]

1. Effect of wind speed and turbulence intensity on summer clothing insulation: A wind tunnel study. Xinzi Xu, Yichen Yu, Cheng Zhao, Qingping Sun, Jianlei Niu. *Indoor air 2026*, June 2026.
2.

[Published books]

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[Other]

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5. Research Group

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6. Abstract (half page)

Research Theme: Effect of wind speed and turbulence intensity on summer clothing insulation: A wind tunnel study

Representative Researcher (Affiliation): Yichen Yu (The Hong Kong Polytechnic University)

Summary・Figures

This study investigated the clothing insulation of tight-fitting (S-size) and loose-fitting (XL-size) clothing using a thermal manikin in a wind tunnel. Tests were performed under different wind speeds, wind directions, and turbulence intensities. Results show that the overall clothing insulation of S-size clothing decreases continuously with wind speed and is independent of wind direction. For XL-size clothing, the overall clothing insulation varies with wind direction: it rises first and then decreases under front and side wind, but declines first and then rises under back wind. Turbulence intensity has little effect on S-size clothing, but significantly increases clothing insulation for XL-size clothing under all wind directions.

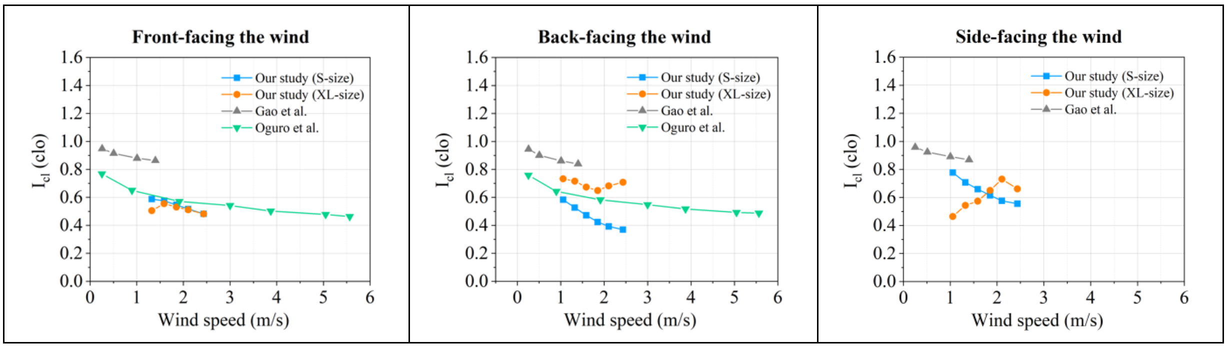

Figure 1. Compare clothing insulation of whole clothed body with other studies in uniform wind conditions.

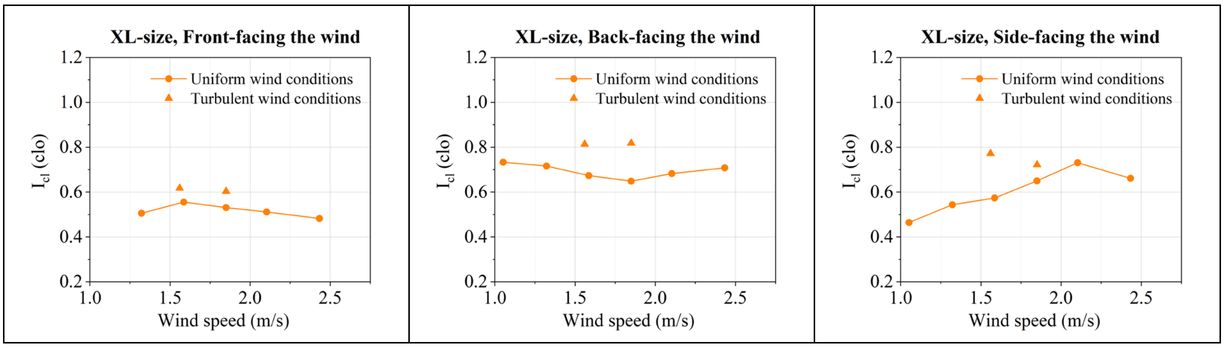

Figure 2. Effect of turbulence intensity on clothing insulation of whole clothed body.