A THERMODYNAMIC MODEL FOR OFFICIAL CLOTHING INSULATION

by

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Clothing insulation is an important factor in the thermal comfort research, and thus an accurate clothing insulation model is much required. This study develops a new model, which takes into account the sex difference for the dress. Its accuracy was verified experimentally, and the established thermodynamic model is useful to predict occupants' clothing behavior and to evaluate thermal comfort.

Keywords: *clothing insulation, running mean outdoor temperature, thermal comfort, outdoor temperature at 6 a. m.*

Introduction

Clothing can be described as a physical term of thermal insulation for the heat exchange of humans with the surrounding thermal environment [1]. In thermal comfort theory, clothing insulation is an important factor that affects thermal sensation [2]. People can adjust their clothing insulation to meet their own thermal comfort requirements [3, 4] and reduce energy consumption in buildings [5]. Clothing adjustment is a powerful behavioral adaption mode to weather changes [6, 7]. It is, perhaps, the most important of all the thermal comfort adjustments available to occupants [8]. Therefore, the clothing insulation model, used to predict clothing behavior based on outdoor temperature, is important for thermal comfort and building energy consumption [9, 10].

Clothing insulation models are usually developed with outdoor temperatures. de Dear and Brager [11] developed models with the mean outdoor effective temperature, and they indicated that 40% of the variance in clothing insulation was explained by the variations in the outdoor climatic index. Haldi and Robinson [12] performed a model with daily mean outdoor temperature throughout the preceding 24 hours, and the model explained 40% of the variation in clothing insulation with the change of outdoor temperature. Carli *et al.* [13] compared outdoor temperature at 6 a. m., mean daily outdoor temperature, mean monthly outdoor temperature, and weighted outdoor temperature over the last four days. They found that the outdoor temperature at 6 a. m. had the highest explanation (31%) for the variation in clothing insulation. Carvalho *et al.* [14] compared daily maximum outdoor temperature and mean temperature of previous days, and they reported that the mean outdoor temperature on the previous day had a higher weight (81%) than the daily maximum temperature (19%) on the clothing insulation. Liu *et al.* [15] used the running mean (RM) outdoor temperature to express past outdoor temperatures and found a very high explanation (91.7%) for the variation in clothing insulation.

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The aforementioned models indicated that the outdoor temperature at 6 a. m. and RM outdoor temperature had a significant impact on clothing insulation. In other words, human clothing behavior was mostly affected by the outdoor temperature they got up in the morning and the outdoor temperature they experienced. However, no research compiled the two temperatures into one model. We assume that a clothing insulation model using the two temperatures will be more accurate. To verify this hypothesis, weighting coefficients for the outdoor temperature at 6 a. m. and RM outdoor temperature were analyzed. The coefficients with the biggest R^2 were used to develop new clothing insulation models. The optimal model was presented by comparing the new and common models.

Methodology

The RM outdoor temperature

The RM outdoor temperature exponentially weights the RM of the past outdoor temperatures to express thermal history. It has been successfully used in the adaption thermal comfort models in the European standard (EN 15251) [16] and several other studies [9, 17]. The RM outdoor temperature is defined by [16]:

$$T_{\mathrm{RM}} = (1-\alpha)(T_{\mathrm{od}-1} + \alpha T_{\mathrm{od}-2} + \alpha^2 T_{\mathrm{od}-3} + \ldots + \alpha^{n-1} T_{\mathrm{od}-n}) \tag{1}$$

where T_{RM} [°C] is the RM outdoor temperature during the calculated days, $T_{\mathrm{od}\text{-}1}$, $T_{\mathrm{od}\text{-}2}\ldots$ [°C] are the 24-hours daily mean temperatures for yesterday, the day before yesterday, and so on, α – the time constant ($0 \leq \alpha < 1$) that quantitatively reflects the rate at which the effect of any past temperature decays.

Alternatively, the following simplified version is [16]:

$$T_{\mathrm{RM}} = (1-\alpha)T_{\mathrm{od}-1} + \alpha T_{\mathrm{RM}-1} \tag{2}$$

where $T_{\mathrm{RM}\text{-}1}$ [°C] is the 24 hours RM outdoor temperature for yesterday.

It was confirmed that the correlation coefficient between the RM outdoor temperature and the observed clothing value was the maximum when α was 0.8 [15, 16]. So 0.8 was used in eq. (2). The data of outdoor air temperatures used in this research were recorded from the Australian Government Bureau of Meteorology website on the day of the observations.

Combined outdoor temperature

Since the outdoor temperature at 6 a. m. and RM outdoor temperature had a significant impact on clothing insulation, a new index of outdoor temperature was presented to combine the two temperatures. It was called combined outdoor temperature and calculated by:

$$T_{\mathrm{co}} = aT_{\mathrm{RM}} + bT_{6\ \mathrm{a.\,m.}} \tag{3}$$

where T_{co} [°C] is the combined outdoor temperature, $T_{6\ \mathrm{a.\,m.}}$ [°C] – the outdoor temperature at 6 a. m., and a and b – the weighting coefficients (0.1-0.9), and their sum is equal to 1. The possible values of a and b are listed in tab. 1.

Table 1. The paired *a* and *b* values

a	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
b	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1

Clothing insulation

The data of clothing insulation were recorded from a longitudinal survey in office buildings of Sydney Australia. The survey was conducted from May 2018 to December 2018, including clothing levels in the late autumn, winter, spring, and early summer. During the whole investigation, staff activities were typing, talking, or meeting. The intrinsic clothing insulation of the composite ensemble was estimated based on [18-22]. A total of 2520 valid samples were used for this analysis.

Statistical analysis

Pearson correlation analysis was used to evaluate the relevance between the indoor clothing insulation and outdoor climatic parameters. The optimal weighting coefficients in eq. (3) and tab. 1 were selected according to the maximum determination coefficient of R^2. The statistical analysis was performed with SPSS 25.0. The significance level was set as $p = 0.05$. A linear regression model was used to express the relationship between indoor clothing insulation and the combined outdoor temperature. In order to compare the new and common models, linear regression models were also used between the clothing insulation and the outdoor temperature at 6 a. m., and between clothing insulation and RM outdoor temperature.

Results

Weighting coefficient

The linear regression models between clothing insulation and combined outdoor temperature were fitted with each pair of weighting coefficient in tab. 1, and the corresponding R^2 were drawn in fig. 1. It was clear that the maximum R^2 was 0.9636, 0.9635, and 0.9383 for the total, female and male observations, respectively, where $a = 0.1$, $b = 0.9$, or $a = 0.2$, $b = 0.8$. the result indicated that the outdoor temperature at 6 a. m. had a higher weight (80~90%) than the RM outdoor temperature (10~20%).

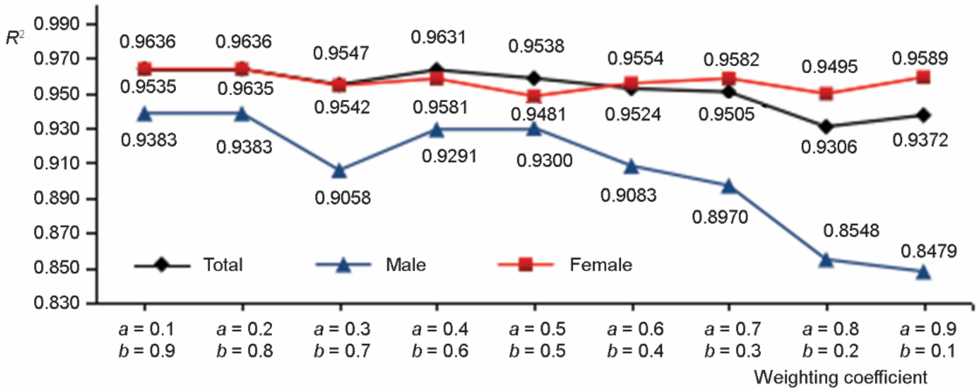


Figure 1. Comparison of weighting coefficients of *a* and *b*

Outdoor temperature

When $a = 0.1$, $b = 0.9$, and $a = 0.2$, $b = 0.8$, the calculated combined outdoor temperatures by eq. (3) were almost the same. Their average relative error was less than 2%. So the combined outdoor temperatures in the following results were calculated using $a = 0.1$, $b = 0.9$.

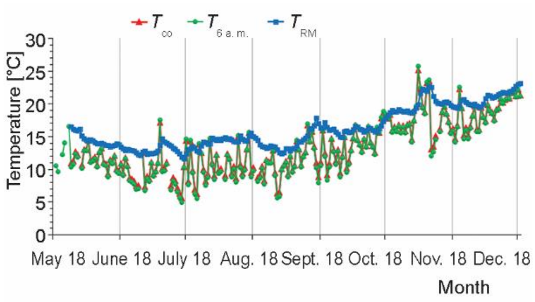
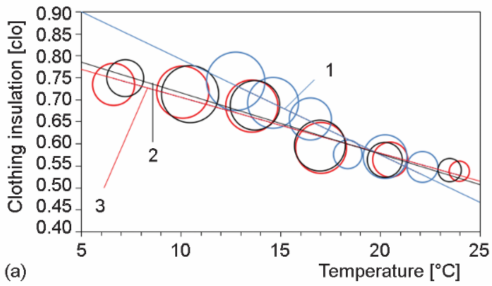


Figure 2. The variation of combined outdoor temperature, T_{co}, RM outdoor temperature, T_{RM}, and outdoor temperature at 6 a. m., $T_{6\ a.\ m.}$

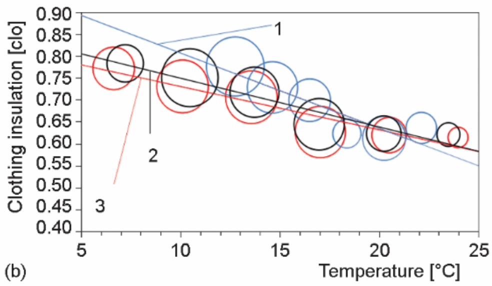
The combined outdoor temperature, RM outdoor temperature, and outdoor temperature at 6 a. m. during the survey months were shown in fig. 2, and their variation scopes were 5.6~25.1 °C, 11.6~23.1 °C, and 4.9~25.7 °C, respectively. The RM outdoor temperature was higher than the combined outdoor temperature, and the outdoor temperature at 6 a. m. was the lowest.

Clothing insulation model

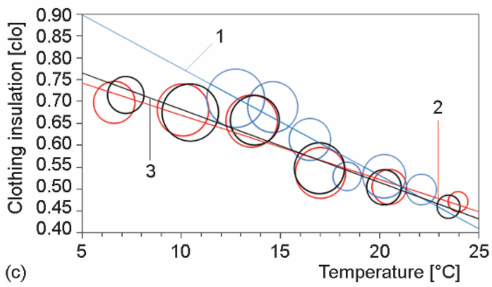
The clothing insulation models with combined outdoor temperature, RM outdoor temperature, and outdoor temperature at 6 a. m., were developed using the linear regression function, as shown in fig. 3. The clothing values varied between 0.43 clo and 0.85 clo. Male staffs had a little higher clothing insulation than females. Female staffs liked fashion clothing, and they almost wore thin or thick dresses during the survey, while male staffs usually wore suits. The clothing insulation of the former was less than that of the latter. The slope of the female clothing model was a little bigger than that of the males. So female staffs were more sensitive to outdoor temperature and changed clothing more frequently than the males.



1 – clo = –0.0217T_{RM} + 1.0081, R^2 = 0.9459, p = 0.000, 2 – clo = –0.0139T_{co} + 0.8546, R^2 = 0.9636, p = 0.000, 3 – clo = –0.0127$T_{6\ a.\ m.}$ + + 0.8322, R^2 = 0.9496, p = 0.000



1 – clo = –0.0172T_{RM} + 1.9786, R^2 = 0.5331, p = 0.000, 2 – clo = –0.0111T_{co} + 0.8606, R^2 = 0.9383, p = 0.000, 3 – clo = –0.0099$T_{6\ a.\ m.}$ + + 0.8292, R^2 = 0.9158, p = 0.000



1 – clo = –0.0245T_{RM} + 1.0201, R^2 = 0.9289, p = 0.000, 2 – clo = –0.01471T_{co} + 0.815, R^2 = 0.9366, p = 0.000, 3 – clo = –0.0167$T_{6\ a.\ m.}$ + 0.8484, R^2 = 0.9635, p = 0.000

Figure 3. Comparison of clothing insulation models between combined outdoor temperature, T_{co}, RM outdoor temperature, T_{RM}, and outdoor temperature at 6 a. m., $T_{6\ a.\ m.}$, for (a) total, (b) male, and (c) female observations

The clothing insulation model with combined outdoor temperature had the maximum R^2 in the three models, whether for the total, male, or female observations. Figure 3(a) indicated that the combined outdoor temperature, RM outdoor temperature, and outdoor temperature at 6 a. m. had the explanation of 96.36%, 94.59%, and 94.96% for the total variation in clothing insulation, respectively. They were 93.83%, 83.31%, and 91.58% for the males, fig. 3(b), and 96.35%, 92.89%, and 93.66% for the females, fig. 3(c). The combined outdoor temperature had the highest explanation in the three outdoor temperatures. Therefore, the new clothing insulation model with combined outdoor temperature was more precise than the other models.

Conclusion

The T_{RM} and $T_{6\text{ a. m.}}$ are usually used separately in the clothing insulation model. In this research, they were combined into one index of outdoor temperature to develop more precise clothing insulation models. The following conclusions were reported as follows.

- When weighting coefficients were a = 0.1, b = 0.9 and a = 0.2, b = 0.8, the calculated combined outdoor temperatures had the highest explanation (96.36%) for the variation in clothing insulation. In the combined outdoor temperature, the outdoor temperature at 6 a. m. had a weight of 80~90%, and RM outdoor temperature had a weight of 10~20%.
- The clothing insulation model with the combined outdoor temperature had the maximum R^2 in the three models whether for the total (0.9636 *vs.* 0.9459, 0.9496), male (0.9383 *vs.* 0.8331, 0.9158), or female (0.9635 *vs.* 0.9289, 0.9366) observations. The presented new models were more precise than the models with only RM outdoor temperature or outdoor temperature at 6 a. m.
- Clothing behavior was different between genders. Women were more sensitive to outdoor temperature and changed clothing more frequently than men.

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