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Indoor clothing insulation and thermal history: A clothing model based on logistic function and running mean outdoor temperature

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ABSTRACT

Predicting the pattern of clothing adjustment to climate change can provide important basis for thermal comfort and energy consumption analysis. This study proposed a clothing model (IC-RM model) to predict indoor clothing insulation based on people's thermal history. In the IC-RM model, the running mean (RM) outdoor temperature (exponentially weighted running mean of the past outdoor temperatures) was used as the outdoor climate index to reflect the thermal history. Different from the existing models, the IC-RM model adopted a four parameters logistic function to fit the relation between indoor clothing insulation and the RM outdoor temperature. A longitudinal thermal comfort survey (13 months) was conducted in two different types of naturally ventilated building in Changsha China. The decreased freedom of clothing adjustment at high/low outdoor temperatures and notable effects of the past outdoor temperatures on the indoor clothing insulation were observed. The IC-RM model was implemented using 1427 useful clothing records collected during the survey. The high R^2 value (> 0.9) for the IC-RM model indicated that the proposed model provides an effective method to quantify the change of indoor clothing insulation based on the effect of thermal history. Compared with linear, exponential and power functions, the logistic function exhibited better performance in quantifying the tendency for the variation in the indoor clothing insulation with the RM outdoor temperature.

1. Introduction

Clothing can be described in physical term of thermal insulation for the heat exchange of man with his immediate 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 suit their own thermal comfort requirement [3,4] and reduce energy consumption in buildings [5]. Therefore, clothing adjustment is a powerful behavioural adaption mode to weather change [6,7]. Predicting the pattern of clothing adjustment to weather change provides important basis for thermal comfort and energy consumption analysis [8,9].

Outdoor temperature is an important climatic factor to the change of indoor clothing. Various models were developed to predict the change of indoor clothing insulation with outdoor temperature, based on different regression functions. de Dear and Brager used an exponential decay function to fit the change of the mean clothing insulation for occupants of each building with the mean outdoor effective temperature at the time of the survey, based on ASHRAE RP-884 database. According to this model, 40% of the variance in clothing insulation was explained by variations in the outdoor climatic index [10]. Nicol et al. developed regression models for the change of mean clothing insulation with daily mean outdoor temperature on the day of the survey, based on the field surveys conducted in five cities of Pakistan [11]. Their results show that the cubic function and the linear function explained 90% and 80% of the variance in clothing insulation, respectively. Morgan and de Dear examined the day-to-day variation in indoor clothing insulation in a shopping mall and a call centre in Sydney, Australia [8]. A power function and an exponential function are developed to reflect the decrease in average clothing insulation with increased mean daily outdoor temperature in the shopping mall and the call centre, respectively. Both model explained about 45–55% of the variance of clothing insulation. Carli et al. used linear regression functions to quantify the relationship between the daily maximum, minimum and mean clothing insulation and four types of outdoor temperatures including outdoor temperature at 6 a.m., mean daily outdoor temperature, mean monthly outdoor temperature and weighted outdoor temperature over the last 4 days, respectively [12]. They found that the outdoor temperature at 6 a.m. gave the highest explanation (31%) for the variation in clothing insulation in naturally

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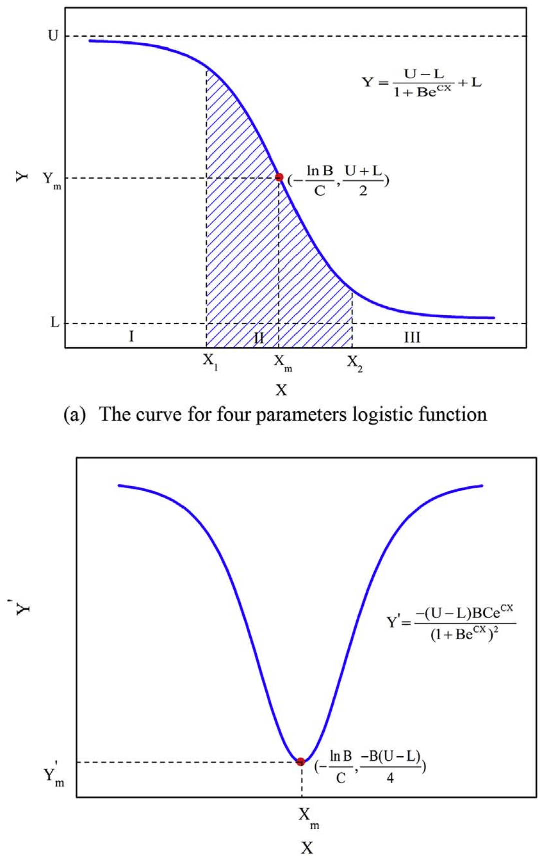
ventilation buildings. Their data was from the RP-884 database and field measurements in Singapore and Indonesia. Haldi and Robinson performed linear regression between clothing insulation and daily mean outdoor temperature throughout the preceding 24 h, using the data from a field survey conducted in Switzerland [13]. The model explained 40% of the variation in clothing insulation due to the change of outdoor temperature. Schiavon and Lee proposed a dynamic clothing model for thermal comfort standard based on 6333 selected observations from ASHRAE RP-884 database [14]. They applied linear and exponential functions to fit the relationship between clothing insulation and outdoor air temperature at 6 a.m., which predicted 19% of the total variance in clothing insulation. Carvalho et al. used linear function to relate clothing insulation with the daily maximum outdoor temperature and mean temperature of previous days, based on a field survey conducted in two naturally ventilated buildings in Leiria, Portugal [15]. Their results showed that the mean outdoor temperature on previous day had a higher weight (81%) than daily maximum temperature (19%) on the clothing insulation.

These above models have two limitations for the prediction on clothing insulation. On the one hand, the linear function, as used by most of the existing models, is not able to reflect the diminished degree of freedom for clothing adjustment with the outdoor temperature becoming high in summer and low in winter. The diminished degree of freedom means that people are less likely to vary the amount of clothing they wear. Though the exponential and power functions described the reduced variation in clothing insulation under high outdoor temperatures, they failed to reflect the similar trend under low outdoor temperatures. These shortcomings restrict the reliability of these models in the prediction of indoor clothing insulation, especially under hot and cold climate conditions. As shown in Fig. 1(a), the curve for the logistic function is accordant to the trend of the clothing insulation with climate change. Therefore, the logistic function is expected to fit the pattern of clothing change better.

On the other hand, these models used current outdoor temperatures as the outdoor climatic index to predict the indoor clothing insulation. However, the fact is that the real time climate information cannot be known in advance. If forecast outdoor temperatures are used, this will cause deviation. Some studies revealed the important effect of the thermal history on the clothing adjustment [e.g. 8, 15]. That is to say, the past outdoor temperatures significantly influence the indoor clothing insulation. Based on such effect, the information on past outdoor temperatures should be able to provide basis to predict indoor clothing insulation. The running mean (RM) of the outdoor temperature (exponentially weighted running mean of the past outdoor temperatures) can well reflect the thermal history, which has been successfully applied in the adaption thermal comfort models for the European standard (EN 15251) [16]. Since clothing insulation is an important factor to thermal comfort, it is expected that the RM outdoor temperature is also suitable for the prediction of indoor clothing insulation. Only a few studies used the RM outdoor temperature as a predictor for indoor clothing [17,18]. However, the details of the calculation for the RM outdoor temperature was not given in these studies. The method to determine the optimal RM outdoor temperature for the clothing change still needs to be investigated.

This study proposed a model to predict the change of indoor clothing insulation based on people's thermal history (past outdoor temperatures). The proposed model used the RM outdoor temperature as the predictor for indoor clothing insulation. Different from the existing models, a four parameters logistic function was adopted to fit the relation between the clothing insulation and the RM outdoor temperature. The proposed model can refine on the shortcomings of the existing models by using the logistic function and well reflect the cumulative effect of the past outdoor temperatures by using the RM outdoor temperature.



(a) The curve for four parameters logistic function

(b) The curve for slope of logistic function

Fig. 1. A four parameters logistic function for indoor clothing model. *Y* means clothing insulation, *Y′* variation rate of clothing insulation and *X* the RM outdoor temperature.

2. Method

2.1. The logistic function for indoor clothing model

People remove or add their clothing with increase or decrease in outdoor temperature to keep thermal comfort. However, there are two limits for the clothing insulation adjustment. On the one hand, clothing removal slows down until clothing insulation reaches the limit of a socially acceptable level at high outdoor temperatures, because wearing too less clothing cannot be accepted by the public, which is called "adaptive saturation" [19]. On the other hand, clothing addition slows down when clothing insulation increases towards the limit of a psychologically acceptable level at low outdoor temperatures, because adding too much clothing can make people feel uncomfortable and inconvenient. The decrease in freedom of clothing adjustment at high and low outdoor temperatures was observed by the existing studies [8,11,13,20] and the present work (see Section "Results").

A four parameters logistic function is suitable to describe the variation in clothing insulation with outdoor temperature, given as follows [21,22].

$$Y = \frac{U - L}{1 + Be^{CX}} + L \tag{1}$$

where *Y* is clothing insulation. *U* and *L* mean upper and lower limits for clothing adjustment, respectively. *X* means outdoor temperature. *B* and *C* are the regression coefficients of the model.

As reflected by the logistic function, the clothing adjustment behaviour can be divided into three sections, which depends on the