Building and Environment 59 (2013) 250–260

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Dynamic predictive clothing insulation models based on outdoor air and indoor operative temperatures

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ARTICLE INFO

Article history:
Received 10 June 2012
Received in revised form
22 August 2012
Accepted 25 August 2012

Keywords:
Clothing
Behavior modeling
Thermal comfort
Dress code
Occupant behavior
Indoor climate

ABSTRACT

Clothing affects people's perception of the thermal environment. Two dynamic predictive models of clothing insulation were developed based on 6333 selected observations of the 23,475 available in ASHRAE RP-884 and RP-921 databases. The observations were used to statistically analyze the influence of 20 variables on clothing insulation.

The results show that the median clothing insulation is 0.59 clo (0.50 clo ($n = 3384$) in summer and 0.69 clo ($n = 2949$) in winter). The median winter clothing insulation value is significantly smaller than the value suggested in the international standards (1.0 clo). The California data ($n = 2950$) shows that occupants dress equally in naturally and mechanically conditioned buildings and all the data has female and male dressing with quite similar clothing insulation levels. Clothing insulation is correlated with outdoor air ($r = 0.45$) and indoor operative ($r = 0.3$) temperatures, and relative humidity ($r = 0.26$). An index to predict the presence of a dress code is developed.

Two multivariable linear mixed models were developed. In the first one clothing is a function of outdoor air temperature measured at 6 o'clock, and the second one adds the influence of indoor operative temperature. The models were able to predict 19 and 22% of the total variance, respectively. Climate variables explain only a small part of human clothing behavior; nonetheless, the predictive models allow more precise thermal comfort calculation, energy simulation, HVAC sizing and building operation than previous practice of keeping the clothing insulation values equal to 0.5 in the cooling season and 1 in the heating season.

1. Introduction

The amount of thermal insulation worn by a person has a substantial impact on thermal comfort [1]. Clothing adjustment is a behavior that directly affects the heat-balance. The thermal insulation provided by garments and clothing ensembles is expressed in a unit named clo, where 1 clo is equal to 0.155 m^2 K/W. For near-sedentary activities where the metabolic rate is approximately 1.2 met, the effect of changing clothing insulation on the optimum operative temperature is approximately 6 °C per clo. For example, adding a thin, long-sleeve sweater to a clothing ensemble increases clothing insulation by approximately 0.25 clo. Adding this insulation would lower the optimum operative temperature by approximately 6 °C/clo × 0.25 clo = 1.5 °C [1]. Clothing adjustment is perhaps the most important of all the thermal comfort adjustments available to occupants in office buildings [2].

Clothing is one of the six variables (others are: Air temperature, mean radiant temperature, air speed, relative humidity and metabolic activity) that affect the calculation of the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) [3] and therefore is an input for thermal comfort calculations according to American [1], European [4] and International [5] thermal comfort standards. In the standards, thermal comfort ranges are usually calculated for clothing insulation equal to 0.5 clo and 1 clo. If other information is not available, thermal comfort evaluations for the cooling season are performed with a clothing insulation equal to 0.5 clo, and for heating season with a clothing insulation equal to 1 clo. The selection of the clothing insulation for thermal comfort calculations affects the design (sizing and analysis) of HVAC systems, the energy evaluation and the operation of buildings. In annual energy and thermal simulations there are no standardized guidelines on how to set clothing insulation schedules. Often, just two values are used (0.5 and 1 clo) and the change from 0.5 to 1 or

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http://dx.doi.org/10.1016/j.buildenv.2012.08.024

vice-versa is done suddenly (from one day to another) and arbitrarily [6].

These simplifications may lead to systems that are incorrectly sized and/or operated. A model that is able to predict how building occupants change their clothing would greatly improve HVAC system operation. Previous attempts to develop a dynamic clothing model demonstrated that the ability to more accurately predict variations in clothing leads to improved thermal comfort [2], smaller HVAC size and lower energy consumption [7].

de Dear and Brager [8] and de Dear [9] analyzed the relationship between clothing insulation and mean indoor operative temperature [8] and mean outdoor effective temperature [8] in the publicly available database developed within ASHRAE research project RP-884 [9]. To study the relationships between clothing level and indoor and outdoor temperatures they used the average building value (160 buildings) and not the value for each occupant (22,346 occupants), i.e. the regression analysis was done with 160 statistical units (one value for each building) and not with 22,346 statistical units. They used the building and not the occupant as unit of the statistical analysis to ensure some homogeneity of conditions affecting each subset of data, but there was not an explicit verification of linear regression assumptions. In Fig. 5b a risk of leverage effect due to four data points (probably outliers) is visible [8]. Using the building as the statistical unit artificially reduces variance and increases the coefficient of determination (R^2). This implies a loss of information. As explained later in the paper, it is possible to take into account the variance caused by the building and use each occupant as the statistical unit by applying regression analysis based on mixed models (fixed plus random effects) instead of linear model (only a fixed effect) [10].

De Carli et al. [7] developed single variable linear regression models to predict the clothing insulation as a function of the outdoor air temperature measured at 6 o'clock in the morning. Independent models were developed for naturally and mechanically air conditioned buildings and for three latitudes ranges. The models were based on the database developed within ASHRAE research project RP-884 [9] and on field measurements performed by Feriadi et al. [11]. Based on energy simulation, De Carli et al. [7] concluded that in mechanically conditioned buildings a variation of 0.1 clo is sufficient to significantly affect the comfort evaluation based on the PMV–PPD model. The developed models have the following limitations: a) the homoscedasticity hypothesis of the developed linear models has not been reported, therefore it is possible that the regression coefficients are not correct [10]; b) the variance introduced by the building was not included in the models; c) all the data from ASHRAE RP-884 was used regardless of the quality of the measurements of the single projects included in the final database and the fact that different standards have been used to quantify the clothing insulation [9]; d) single variable regression models were used, losing the opportunity to check for interaction effect and the combination of several variables at the same time; and e) it is not clear if other relevant variables, such as air velocity and relative humidity were considered.

Morgan and de Dear [12] examined clothing behavior and its relationship with thermal environments in two indoor settings (shopping mall and call center) located in Sydney, Australia. They found that day-to-day variation in clothing levels changed significantly in the shopping mall where a dress code was not in place. Clothing varied less in the call center where a dress code was enforced. For the shopping mall they developed a linear regression equation to relate the daily average clothing value with daily mean outdoor dry bulb temperature.

The aim of this research is to develop dynamic, i.e. changing daily or hourly, predictive models of clothing insulation typically used by office occupants to be applied in thermal comfort calculation, HVAC sizing, building energy analysis and building operation.

2. Method

2.1. Database

The data to develop the model were taken from ASHRAE RP-884 [9] and from ASHRAE RP-921 [13] databases. These public-domain databases contain quality-controlled data from thermal comfort field studies conducted in various countries and climate zones around the world. The two research projects are, to the knowledge of the authors, the biggest published and publicly available collection of thermal comfort field measurements. The RP-884 is the basis for the development of the thermal comfort adaptive model used in ASHRAE 55 [1]. The thermal comfort questionnaires were accompanied by simultaneous and local indoor climate measurements (e.g. air temperature, mean radiant temperature, air speed and humidity, etc.). All the data from ASHRAE RP-921 have been used. Data in ASHRAE RP-884 were classified by the authors of the report into three levels of quality (from Class I, the best, to Class III, the lowest quality data). In this research only data of Class I were used because they were collected with 100% compliance with the specification set out in ASHRAE Standard 55-1992 and ISO 7730-1984 (see Paragraph 2.2.2 of [9]). ASHRAE RP-921 complies with the same standards, and therefore it fits with Class I.

Thermal comfort standards (e.g. ISO 7730 and ASHRAE 55) provide techniques to evaluate the clothing insulation. A problem faced in ASHRAE RP-884 [9] was that standards, in their various revisions, have used different techniques, leading to quite different clothing estimates to be calculated for a given set of clothing, depending on which standard and which edition was used. To solve this problem, the researchers converted the different clothing estimation techniques into equivalent ASHRAE Standard 55-92 [14] clothing estimates. In this research only clothing values calculated using ASHRAE Standard 55-81 [15] and ASHRAE Standard 55-92 [14] were used (see Table 1). De Dear et al. [9] estimated, in the conversion from ASHRAE Standard 55-81 to 92, that for male and female the regression equation was able to explain 81% and 61% of the variance ($R^2 = 0.81$), respectively. We kept the data collected with the two methods in order to have a bigger sample (6333 observations instead of 3298). The clothing values used here are calculated according to ASHRAE Standard 55-92 [14] and do not

Table 1
File identification number, standard used to estimate the clothing insulation, sample size and number of buildings of the data used in this research.

File number[a]	City, state and season	Clothing method	Sample size	Number of buildings
5	Antioch, California (winter)	ASHRAE 55-81	111	1
9,10	Montreal, Canada (summer and winter)	ASHRAE 55-92	869	23
32,33,34,35	Bay Area, California (summer and winter)	ASHRAE 55-81	2330	20
36,37	Townsville, Australia, (dry and wet season)	ASHRAE 55-92	1231	23
43	Grand Rapids, Michigan (winter)	ASHRAE 55-81	85	1
44,45	San Ramon, California (summer and winter)	ASHRAE 55-81	381	3
46	Aubum, California (winter)	ASHRAE 55-81	128	1
47,48	Kalgoorlie, Australia (summer and winter)	ASHRAE 55-92	1198	22

[a] File number: identification of the file according to [9] and [13].