The Impact of the Two Predictive Clothing Insulation Models on Building Energy Performance

K. H. Lee[1,*] and S. Shciavon[2]

[1]Department of Architectural Engineering, Hanbat National University, Daejeon 301-719, South Korea
[2]Center for the Built Environment, University of California,
Berkeley 94720, USA

ABSTRACT

In the HVAC system energy simulation, indoor thermal comfort condition is typically calculated based on the assumption that the clothing insulation is equal to a constant value of 0.5 clo during the cooling season and 1.0 clo during heating season. In reality, occupants frequently adjust their clothing depending on the thermal conditions, as opposed to the assumption of constant clothing insulation, indicating that the clothing variation should be captured during the building simulation to realistically model HVAC systems. In this study, the impact of the two newly developed predictive clothing insulation models on the HVAC system operation and energy consumption is quantitatively assessed using the detailed whole-building energy simulation program, EnergyPlus. The first model varies the clothing insulation as a function of outdoor air temperature measured at 6 am and the second model takes into account both 6 am outdoor air temperature and indoor operative temperature when adjusting the clothing insulation. The results of the typical assumption of the constant clothing insulation values were compared to those of the two predictive clothing models. It turned out that more accurate prediction of variations in clothing lead to an increase in the heating energy consumption. This is due to the fact that occupants took less clothing compared to the typical assumption of constant clothing value of 1.0 during the heating season.

KEYWORDS

Predictive Clothing Model, PMV, Building Energy, EnergyPlus, Thermal Comfort

INTRODUCTION

The amount of thermal insulation worn by a person has significant influences on thermal comfort (ASHRAE 2010) and clothing is one of the most important thermal comfort adjustments available to building occupants (Newsham 1997). Clothing value

* Corresponding author email: kwhlee@hanbat.ac.kr

is one of the six variables affecting the determination of the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) (Fanger 1970) and thus it is an important input for thermal comfort determination in a variety of international standards (ASHRAE 2010, CEN 2007, ISO 2005). In addition, clothing insulation significantly affects the design, operation and energy consumptions of HVAC systems when performing the energy simulation (Lee at al. 2012).

Due to the significance of the clothing in the thermal comfort and the HVAC system operation, a number of studies have been carried out (Lee at al. 2012). However, the realistic clothing adjustment by occupants has not been captured in the energy simulation studies. In most building energy simulations, thermal comfort condition is calculated based on the assumption that the clothing insulation is equal to a constant value of 0.5 clo during the cooling season and 1.0 clo during heating season. Only those two values are used and the change from 0.5 to 1 or vice-versa is made suddenly from one day to another (Schiavon et al. 2012). In addition, there is no standardized guideline on how to set clothing insulation schedules in the international standards. The assumption is not reflected in practice and thus it may lead to systems that are incorrectly sized and operated (Schiavon et al. 2012). In reality, occupants frequently adjust their clothing depending on the thermal conditions around them as discussed in other literature above, as opposed to the assumption of constant clothing values. Therefore, the clothing insulation variation should be captured during the building simulation to realistically model HVAC systems (Lee at al. 2012).

In order to overcome the limitations of the constant clothing insulation assumption, two new predictive clothing insulation models were developed by Schiavon et al. based on 6,333 selected observations taken from ASHRAE RP-884 and RP-921 databases (Schiavon et al. 2012, De Dear et al. 1997, Cena et al. 1999). The first model varies the clothing insulation as a function of outdoor air temperature measured at 6 am and the second model takes into account both 6 am outdoor air temperature and indoor operative temperature when adjusting the clothing insulation. The two newly developed predictive clothing insulation models are implemented into the detailed whole-building energy simulation program, EnergyPlus version 6.0 (Lee at al. 2012). Using the customized version of EnergyPlus, the impact of the two predictive clothing insulation models on the HVAC system operation and energy consumption is quantitatively assessed. The detailed results such as clothing insulation variations and their impacts on energy consumptions are analyzed and compared between the case assuming the constant clothing insulation values and the cases applying those two new predictive models (Lee at al. 2012).

RESEARCH METHODS

Two new predictive clothing insulation models were developed by Schiavon et al. based on 6,333 selected observations taken from ASHRAE RP-884 and RP-921 databases (Schiavon et al. 2012). There are a variety of possible variables that may affect the clothing insulation such as sex, HVAC system type, indoor operative temperature, relative humidity, outdoor condition, air velocity, season and location, etc. The full list of the variables that were statistically investigated for the screening process is summarized in the work by Schiavon et al. 2012. Multivariable mixed models were used to develop the correlation equations. Among the variables that can possibly affect occupants' clothing, outdoor air temperature measured at 6 am and indoor operative temperature are chosen due to their highest correlations. Two predictive models are reported in the following equations (1) and (2) (Schiavon et al. 2012, Lee at al. 2012).

$$log_{10} clo = -0.1635 - 0.0066 day06\_ta \tag{1}$$

$$log_{10} clo = 0.2134 - 0.0165 top - 0.0063 day06\_ta \tag{2}$$

Where, clo is the clothing insulation value, day06_ta is the outdoor air temperature measured at 6:00 and top is the operative temperature. Those two predictive clothing insulation models are implemented into the customized version of EnergyPlus 6.0. More details regarding the implementation and validation process are described in the work by Lee et al. 2012.

A three-story prototype office building located in Chicago, Illinois having a rectangular shape and aspect ratio of 1.5 was chosen for this study. The floor plate size is 2,000 m^2 (total floor area is 6,000 m^2) and each floor is composed of an interior zone and 4 perimeter zones with the perimeter zone depth of 4.6 m. The floor to floor height is 3.96 m and the return plenum height is 1.0 m. Strip windows are evenly distributed in the walls and the window-to-wall ratio is 40% (Lee at al. 2012). The constructions and the thermal properties of windows comply with ASHRAE 90.1-2004 (ASHRAE 2004).

The interior lighting of 10.8 W/m^2, occupancy of 22.3 m^2/person and the plug load of 8.6 W/m^2 were assumed as the peak internal load levels and the hourly variations of the internal loads for the typical office building follow the schedules specified in ASHRAE Standard 90.1 (ASHRAE 2004). HVAC systems operate from 5:00 through 19:00 during the weekdays.

PMV will be used as the indoor set-point to quantitatively evaluate the impact of the new clothing insulation models in this study. The cooling and heating PMV set-points were set at 0.5 and -0.5, respectively, from 5:00 till 19:00. The HVAC system is switched off during the night-time (Lee at al. 2012). The infiltration was assumed equal to 0.000333 m3/(s m2) (flow per exterior surface area). The minimum outdoor air flow rate was set to be 0.762 L/s•m2 at both system and zone levels. Each zone is served by the conventional variable air volume (VAV) terminal unit. EnergyPlus object of AirTerminal:SingleDuct:VAV:Reheat is used for the realistic modelling of VAV unit (U.S. DOE 2010). At the system level, a single variable-speed central station AHU serves the building and is composed of economizer, chilled water cooling coil, hot water heating coil and supply fan. AHU SAT was set to be 14.0 ℃. The central plant consists of a centrifugal chiller, a gas fired boiler, variable speed pumps and a two-speed cooling tower (Lee at al. 2012).

The purpose of the study is to investigate the influence of the two newly developed clothing insulation values on the HVAC system operation and energy (Lee at al. 2012). Three cases were studied. The baseline (Case 1) is the case applying the assumption of constant clothing values that has been commonly used in the typical energy simulation. More specifically, the clothing insulation is fixed at 0.5 from April 1st through Sep. 30th and is fixed at 1.0 during the rest of the year. Case 2 is one of the two new models relating the clothing insulation to the outdoor air temperature measured at 6 am, which is expressed in Eq. (1). Case 3 is the other new clothing model relating the clothing insulation to both 6 am outdoor air and indoor operative temperatures, which is expressed in Eq. (2). The summary of the simulated cases are provided in Table 1 (Lee at al. 2012).

Table 1. *Summary of the simulated cases*

Case	*Clothing model*
1	Scheduled (Assumption of constant clothing insulation)
2	Equation (1)
3	Equation (2)

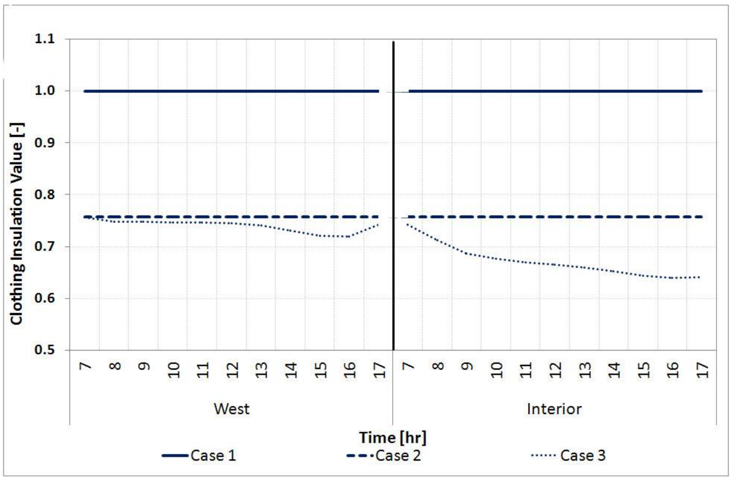

Figure 1*. Hourly clothing insulation variations in the middle floor (Jan. 14th)* (Lee at al. 2012)

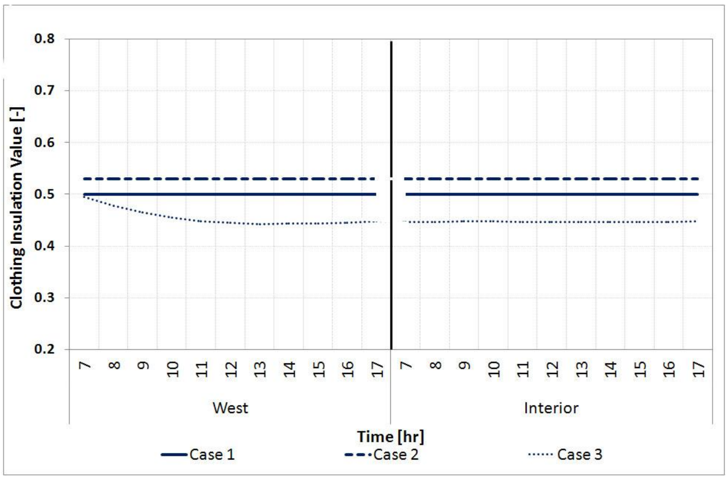

Figure 2*. Hourly clothing insulation variations in the middle floor (Aug. 12th)* (Lee at al. 2012)

RESULTS AND DISCUSSION

Hourly clothing insulation variations in the representative days of winter and summer are illustrated in Figure 1 and 2, respectively. Each figure includes clothing variations in both west perimeter and interior zones for the three simulated cases. Regardless of the season and zone orientation, Case 1 and Case 2 showed constant values during the whole day due to the fact that Case 1 assumed the fixed value depending on the season and that Case 2 adjusted the clothing insulation as a function of 6 am outdoor air temperature, which changed on the daily basis instead of hourly or sub-hourly basis (Lee at al. 2012). On the other hand, in Case 3 where the clothing insulation changed as a function of both 6 am outdoor air and indoor operative temperatures, it changed hourly as shown in Figures 1 and 2, since the indoor operative temperature changed every time-step, which, in turn, directly affected clothing values in each time-step (Lee at al. 2012). More importantly, winter season showed the large difference in the clothing insulation among three simulated cases as shown in Figure 1 (Lee at al. 2012). The clothing in Case 1 was fixed at 1.0 in the winter season, while it was 0.76 in Case 2 and it reached as low as 0.64 in the late afternoon in Case 3. Therefore, the difference between Case 1 and Case 3 reached as 0.36, which is significant (Lee at al. 2012). On the other hand, the difference in the clothing insulation between simulated cases in the summer season did not exceed 0.08 as shown in Figure 2, indicating that the significant difference in the clothing during the winter compared to other seasons can directly affect the heating energy if PMV is used as the indoor control set-point (Lee at al. 2012).

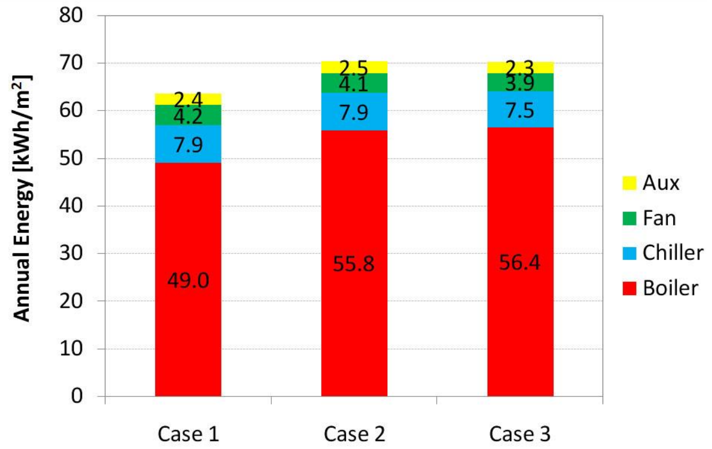

***Figure 3**. Annual energy usage* (Lee at al. 2012)

The annual site HVAC energy breakdown for each simulated case is illustrated in Figure 3. Auxiliaries in the figure include pumps and cooling tower electricity consumptions. As shown in the figure, Case 1 showed the lowest total HVAC energy consumption compared to Cases 2 and 3 mainly due to the lowest annual boiler energy (Lee at al. 2012). This is due to unnecessarily higher clothing insulation in Case 1 as shown in Figure 1 earlier. This suggests that the constant clothing insulation assumption can lead to the under-prediction of the annual heating energy consumption by 15% and that the predictive clothing model taking into account the surrounding thermal environment should be used during the simulation (Lee at al. 2012).

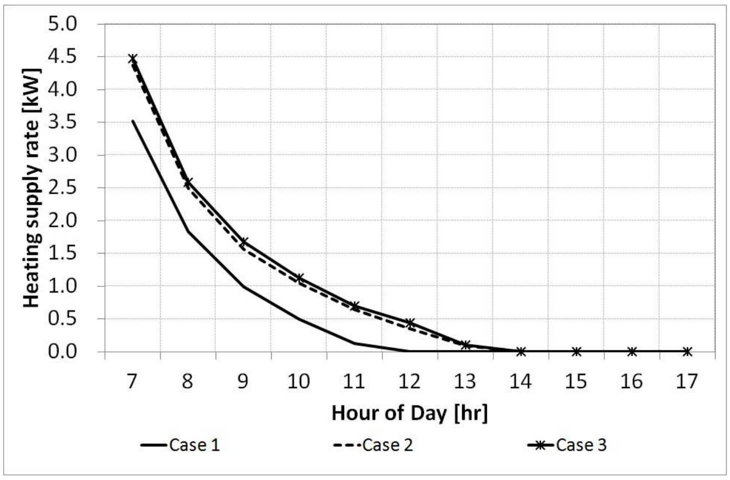

Figure 4. *Hourly supplied heat by the system in the middle floor west zone (Jan. 14th)* (Lee at al. 2012)

Figure 4 illustrates hourly heating supply rates of three simulated cases in the middle floor west perimeter zone in the typical winter day. Heating supply rate is the amount of heating demand that should be provided by the system to meet the PMV heating set-point of -0.5, which is the same as the heating load (Lee at al. 2012). As shown in the figure, Case 1 of the constant clothing insulation fixed at 1.0 clo showed the lowest heating rate compared to Case 2 and Case 3 due to the fact that occupants wore the clothing of 1.0 clo which was higher than the realistic Case 2 and Case 3 as shown in Figure 1 (Lee at al. 2012). In Case 2 and Case 3, occupants take less clothing compared to Case 1 and thus more heating is needed to meet the PMV set-point of -0.5, indicating that the constant clothing insulation assumption fixed at 1.0 clo during the whole winter season can result in the under-prediction of the heating rate and that the accurate variation of the clothing value should be taken into account to realistically model the HVAC system and thermal comfort (Lee at al. 2012).

CONCLUSIONS

In this study, the two newly developed predictive clothing insulation models are implemented into the customized version of the detailed whole-building energy simulation software EnergyPlus. The impact of the two predictive clothing insulation models on the HVAC system operation and energy consumption is quantitatively assessed. The following conclusions were drawn.

- The case with the constant clothing insulation fixed at 1.0 clo during the whole heating season showed the lowest heating supply rate due to the fact that occupants wore the heavier clothing of 1.0 clo than the other realistic cases.
- The case with the constant clothing insulation fixed at 1.0 clo during the heating season showed the lowest annual HVAC energy consumption due to the lowest

annual boiler energy. This was due to unnecessarily higher clothing insulation and lower heating supply rate, indicating that the constant clothing insulation assumption lead to the under-prediction of the annual heating energy consumption by 15%.

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