EFFECTS OF CONVECTIVE HEAT TRANSFER COEFFICIENT ON THE ABILITY OF PCM TO REDUCE BUILDING ENERGY DEMAND

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ABSTRACT

ASHRAE Standard 140-2001 (BESTEST), case 600, in Toronto is simulated in TRNSYS 16. The incorporation of phase change material (PCM) with Type 204 into the BESTEST Case 600 envelope is modelled. PCM layer of one and ten millimetres thick covers all of the wall and ceiling surfaces. Simulations are conducted for different inside convective heat transfer coefficients (h-value). To do this, h-value is changed from 0.5 to 10 W/m^{2}K. All simulations consider Toronto-716240 weather conditions with set points of 21℃ (heating) and 24℃ (cooling). The hourly, monthly and annual energy demand investigation reveals that the heating energy demand increases when h-value increases, but cooling load slightly decreases.

INTRODUCTION

Net zero energy building (NZEB) is the subject of so much research in the last half a century. To reach that goal, energy demand of the building shall be minimized without trading off the environmental comfort for living. Energy demand of a building depends on so many factors, such as: temperature difference between outdoor and indoor, thermal conductivity of the building envelope, thermal mass of the building, internal and external convective heat transfer. Adding a phase change material (PCM) increases the thermal mass and decreases the energy demand of the building. The internal convective heat transfer (h-value) is easy to control and monitor. So by increasing the popularity of the PCMs, users are interested to know what value of h is the most effective when PCM is part of the interior layer of building envelope. This paper investigates the effects of h-value on the effectiveness of the PCM in reducing the energy demand of the building.

Theoretically, as h-value increases the heat transfer between PCM surface and indoor air increases, but the relationship between h-value and energy demand of the building is more complicated. To investigate this relationship TRANSYS 16 simulation software is used. Usually simulation software developers are interested in values or equations of heat transfer coefficients estimated separately for radiation and convection (Causone et al., 2009). In this paper, effects of convective heat transfer coefficient on PCM effectiveness are investigated. TRNSYS 16 is used as the simulator incorporated with phase change material (PCM) Type 204 module.

Natural (free) convection has significant influence in various engineering applications. Therefore, it has been an important research area for over a century. Primarily, natural convection is the dominant mechanisms of heat transfer inside buildings. During the day, the outdoor surface of the envelope receives incident solar radiation, so the interior surface temperature rises as a result of heat conduction from the exposed outer surface, direct solar gains and other internal heat gains (e.g., people and heat generating machines) (Dascalaki et al., 1994). The thin air layer in contact with interior hot surface absorbs heat from the hot surface and becomes lighter and begins to rise due to buoyancy force. The boundary layer region next to the surface controls air velocity and temperature changes.

Natural convection heat transfer is the main heat transfer mechanism occurring from the building surfaces. Assuming no ventilation, due to a temperature difference between the indoor air and the interior building's surface, heat is naturally convected to the indoor air. Therefore, in order to investigate thermal performance of a building it is necessary to understand the convection processes and in particular to estimate the natural heat transfer coefficient. Fundamentally, the h-value is one of the main parameters for load (heating or cooling) calculation, transient thermal simulation and computational fluid dynamics (CFD) analysis (Causone, et al. 2009).

Thermal comfort and energy savings are two major concerns in building science and engineering. These requirements come from strict regulatory rules as well as growing global environmental concerns. Practically, the level of indoor air quality or thermal comfort depends heavily on the characteristics of the building envelope (wall and window insulations, air leakage, etc) and on the outdoor (atmospheric) conditions (solar heat gains, wind velocity, air temperature and humidity, etc). The combinations of all these parameters (external, within the envelope and internal) control heat exchanges between the interior and the exterior of a building and, consequently, affect the overall energy consumption.

It is convenient, in building simulations, to assume that the room air is well-stirred so that a constant air temperature (T_∞) is used. The Newton's law predicts average convective heat flux (q) from the PCM surface as:

$$q = h(T_s - T_\infty) \quad (1)$$

where T_s is the surface temperature and h is the average convective heat transfer coefficient.

In order to calculate average convective heat flux (q), h-value shall be estimated because T_s and T_∞ are possible to measure. In the literature, several h-values and its equations are given between the interior building surfaces (PCM surface either heated or cooled), and the space (average indoor air temperature).

Reviews in literature and experimental findings (Khalifa and Marshall, 1990) help estimate the h-value by monitoring the air speed: h = 5.34+3.27u = $C\Delta T^n$ (u is the air speed in m/s and $\Delta T$is the temperature difference between air and the surface in K). The experimental results for forced convection tests is summarized in Table 1 (Khalifa and Marshall, 1990):

Table 1
Summary of the experimental results for forced convection tests (Khalifa and Marshall, 1990)

AIR SPEED (M/S)	EXPERIMENTAL H-VALUE	RANGE OF H-VALUE IN THE LITERATURE
0.6	7.52	2.3 to 10.1
1.1	8.44	4.3 to 11.5
1.5	10.52	5.9 to 12.4

In defining comfort conditions in ASHRAE Standard 55, operative temperature (T_{op}) is used. It is the average of the mean radiant (T_{mrt}) and ambient air (T_∞) temperatures, weighted by their respective heat transfer coefficients (McQuiston et al., 2005). In TRNSYS 16, the operative room temperature is a function of both the air and surface temperatures in the zone:

$$T_{op} = A*T_\infty + (1-A)*T_s \quad (2)$$

where A is a weighting factor between 0 and 1.

TRNSYS Type 204 PCM Component

Type 240 is a storage model for TRNSYS 16, which is capable of treating microencapsulated PCM-slurries as storage medium as well as storage integrated modules of PCMs of various shapes (cylinders, spheres, plates). There are some validations for Type 240 as storage materials in literature (Schranzhofer et al., 2006). Also Type 241 is gaining significant interest as a layer attached to the wall. Type 204 has been used in the Sustainable Energy lab at Ryerson University; therefore it is accessible option for continuing the research on this type.

Prior to the development of the TYPE 204 model in TRNSYS, it was impossible to directly simulate the effect of heat transfer through a wall containing PCM. While in the past, most of the work was focused on the experimental analysis of building integrated PCM, more recently, with the development of robust building simulation software, it is now possible to investigate in detail the thermal properties of a wide variety of phase change materials without the need for elaborating experimentation. Building simulation also provides a valuable tool for generalization of the experimental data. Moreover, the only manner in which the effects of PCMs in buildings can be investigated is through the development of an active layer within the building envelope. Ibanez et al. (2005) presented a methodology in TRNSYS whereby, through the definition of an active wall containing tubes through which a fluid was circulated, the overall thermal effect of phase change materials could be determined. Even though this approach did not simulate the real heat transfer process through a PCM wall, the overall impact in terms of energy transfer was quite similar to what would be expected with a PCM integrated wall (Ibanez, et al. 2005).

The TYPE 204 component was developed in FORTRAN and integrated into TRNSYS by a team based at the Helsinki University of Technology, Finland (Lamberg et al., 2004). Utilizing the finite difference method with a Crank-Nicholson scheme, the model simulates heat transfer through a 3-D PCM composite wall component containing a total of 729 nodes (9 nodes each in the *x*, *y* and *z* directions). At each node the conduction, convection and radiation heat transfer along with the temperature is calculated (Ahmad, et al. 2006). The 3-D wall element can be defined precisely to specify the concentration and melting points of the PCM used. The properties of the composite building materials used in conjunction with the PCM can also be easily defined. To account for the changes in the specific heat capacity of the PCM due to temperature variations, the model uses the effective heat capacity ($C_{pe} = C_p + \frac{\text{Latent Heat}}{\text{Phase Change Temperature Range}}$) method to define the heat capacity at each phase, i.e., liquid or solid.

The Type 204 PCM module in TRNSYS has the following input parameters that must be entered into the model to accurately represent a particular phase change material. These properties are described in details below:

- Number of Iterations: This parameter can be given any value between one and infinity and is used primarily for the sake of accuracy. Utilizing any number more than one for iteration would involve the solution of relevant heat transfer equations multiple times and generally provide more accurate solutions. The only drawback is increased computation time.

To find a reasonable value for the number of iterations, some preliminary simulations were conducted on ASHRAE Standard 140-2001 (BESTEST) Case 600. Total energy demand to keep the indoor air temperature of the Case 600 in range of 21°C to 24°C versus the number of iteration is plotted in Figure 1. Three iterations provide reasonably good accuracy in this work. The maximum difference between the best number of iteration (20) and 3 is about 5%. The best fit regression (using root square method) is:

$$y = -600.4e^{-0.15x} + 7913.6 \qquad (3)$$

where x is the number of iterations and y denotes the annual energy demand in kWh.

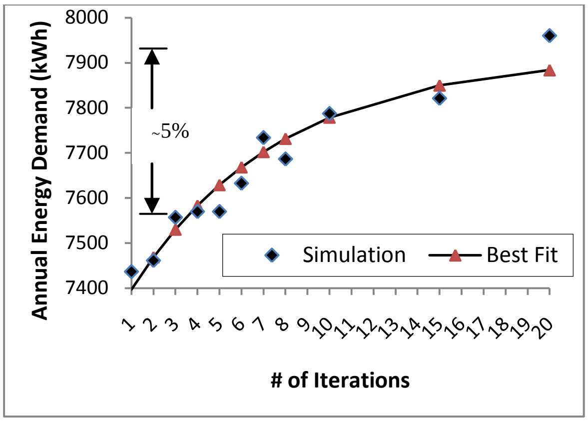

Figure 1 Effect of increasing iteration on ASHRAE Standard 140-2001, Case 600, annual total energy demand

- Melting Temperature: This characteristic is concerned with the initial temperature during which the phase change material undergoes phase transition.
- Crystallization temperature: The crystallization temperature is determined by the point where the PCM changes phase back to a solid. This temperature is always lower than the melting temperature. This is considered one degree lower than melting point. Start and end of melting temperatures considered 22 and 23°C respectively.
- Range in crystallization temperature: Unlike pure materials such as water, which changes phase at a distinct temperature of 0°C, most phase changes undergo the phase change process within a temperature range. This parameter could be used to define the phase change range of a particular PCM.
- Latent heat of PCM: This parameter measures the total heat storage / release capacity of a particular phase change material at the phase change temperature.
- PCM Density: The density of the pure PCM can be entered into the model using this parameter. It is 800 kg/m^3 for DAL HSM (Poulad et al., 2011).
- PCM C_p: This parameter is concerned with the specific heat capacity of the PCM. It is an important characteristic since it provides a measure of the energy storage/release capacity of a particular PCM at a temperature outside the temperature range of phase transition. It is 1.6 J/gK for DAL HSM PCM (Poulad et al., 2011).
- Density of other material in PCM Node: The density of any other materials that has been integrated with the PCM can be entered through this parameter. In this simulation, no other material is used.
- C_p of other material: The specific heat capacity of any other materials incorporated with the PCM can be entered through this parameter.
- Volume fraction of PCM in Node: The overall concentration of PCM in a particular specimen can be entered through this parameter. Since most studies characterize the overall concentration of PCM by weight, this value must be converted into volume fraction to reflect the input requirements of the parameter. For massless simulation, PCM is not mixed; therefore, volume fraction is 1.
- Set point in summer and winter is considered 24°C and 21°C respectively. This is only applicable for investigating energy demand.
- To add the PCM Type 204 to TRNSYS, the following parameters were fixed in the text file named "ALKU":

1. The number of nodes (i, j, k), (fixed) 9*9*9 = 729
2. Dimensions of the wall component, [m]: 0.45, 0.45, 0.2 [meters], height (j), width (i) and depth (k)
3. Convective heat transfer coefficient of the surface of the wall component, the intention of the work is to investigate the effects of change of this parameter (HILMA) from 0.5 to 10 W/m^{2}K). The h-value in the TRNBuild module of TRNSYS was changed accordingly.
4. Time step = 300 second (LASVALI)
5. Weighting factor of finite-difference method (The Crank-Nicholson method: MENKERROI = 0.5)
6. Initial temperature of the nodes = 20 °C
7. Indoor temperature (fixed) = 40 °C
8. Initial value of effective heat capacity C_T = 2500 J/kg-K (Poulad et al., 2011).

SIMULATION RESULTS

The simulation is conducted with TRNSYS using Type 204 PCM module developed in Helsinki, Finland. Energy consumption of the ASHRAE Standard 140-2001 (BESTEST) Case 600 with PCM is calculated with different h-values to investigate its effect on the energy consumption of the house. The energy demand is simulated using Toronto weather conditions. Results are given as plots of energy demand versus h-value. The h-value, which transfers heat between the PCM layer and the indoor air, is changed from 0.5 W/m^{2}K to 10 W/m^{2}K. The sensitivity of the energy demand on the h-value is given in two sections:

1. Effects of h-value on the Cooling Energy Demand. Cooling energy demand is investigated in three different occasions. In all occasions, operative temperature is found to be about 25℃ where it is used:

- at the warmest outdoor temperature hour, which is 4839 (on 21th of July)

Figure 2 illustrates the cooling load variation with h-value at the warmest hour of the year. The best fit curves are also added to the plots; the slope of the trendline or tangent to the graph at any h-value indicats the sensitivity of energy demand to the h-value. The graph shows that the sensitivity increases with PCM reduction (from 3 hm^{2}K, slope of linear trendline, to 115 hm^{2}K, dotted line, with 10mm PCM and no PCM respectively). The curves for 1mm PCM and 10mm PCM are plynomials with power six and five, respectively.

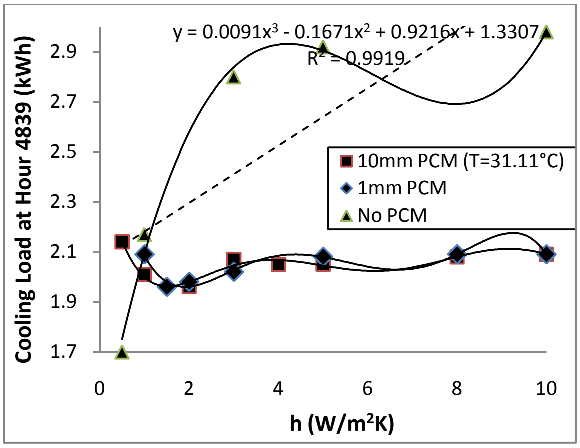

Figure 2 Effect of h-value on cooling energy demand at the warmest hour (4839) of the year

- in August (from hour 5080 to 5832), the cooling load is at its maximum with respect to other months of the year

Figure 3 illustrates the cooling load variation with h-value in the warmest month of the year. The best fits are also added to the plots. Again, the sensitivity increases with PCM reduction (from -1.2327 hm^{2}K to 19.032 hm^{2}K, assuming linear trendline) with 10mm PCM and no PCM respectively. Another point is that cooling load decreases as PCM thickness (amount) increases. The best fits for 1mm PCM and 10mm PCM are both plynomials with power five.

- and finally, annual cooling load

Figure 4 illustrates annual cooling load variation with h-value. The trend lines are also added to the plots. Again, the sensitivity increases with PCM reduction (from -2.819 hm^{2}K to 150.73 hm^{2}K, assuming linear trendline) with 10mm PCM and no PCM respectively. Obviousely, cooling load decreases as PCM thickness (amount) increases. In all three cases, when h equals to 0.5 W/m^{2}K, presence of the PCM is not in favor of energy demand reduction. The curves for 1mm PCM and 10mm PCM are plynomials with power three and six, respectively.

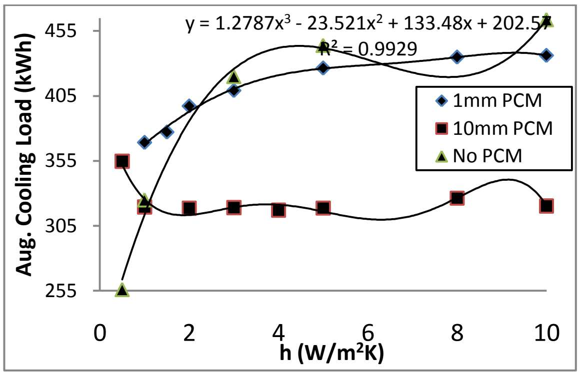

Figure 3 Effect of h on cooling energy demand in the warmest month of the year, August

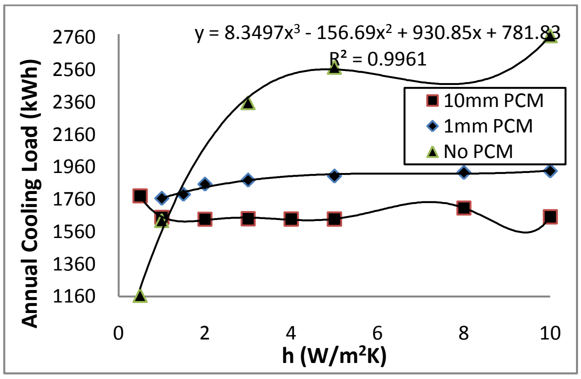

Figure 4 Effect of h on annual cooling energy demand

2. Effects of h on the Heating Energy Demand. Heating energy demand is also investigated on three different occasions:

- at the coldest hour, which is 289 (on 13th of January)

Figure 5 illustrates the heating load variation with h-value at the coldest hour of the year. The best fits are also added to the plots. The graph shows that the sensitivity is the lowest with 1mm PCM (7.3 hm^{2}K, assuming linear trendline). The maximum sensitivity goes to no PCM condition again. In addition, heating load demand is reduced for 10mm PCM with respect to 1mm PCM and no PCM conditions. The best fits for 1mm PCM and 10mm PCM are both plynomials with power five.

- in February (from hour 744 to 1416), the heating load is the maximum with respect to other months of the year

Figure 6 illustrates the heatling load variation with the h-value in the coldest month of the year. The best fits are also added to the plots. The graph shows that the sensitivity is the lowest value with 1mm PCM (7249 hm^{2}K, assuming linear trandline). Again, the maximum sensitivity goes to no PCM condition. In addition, heating load decreases as the PCM amount (thickness) increases. The best fits for 1mm PCM and 10mm PCM are both plynomials with power four.

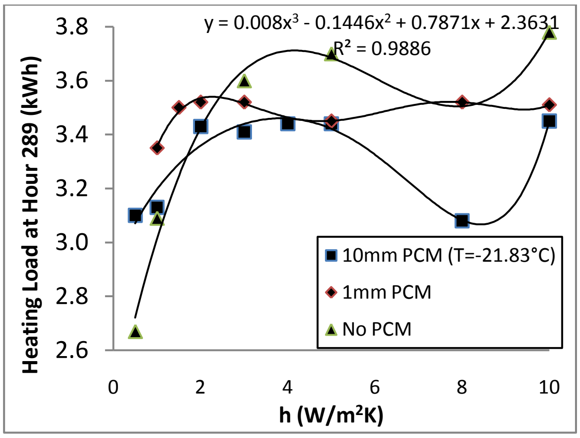

Figure 5 Effect of h on heating energy demand at the coldest hour (289) of the year

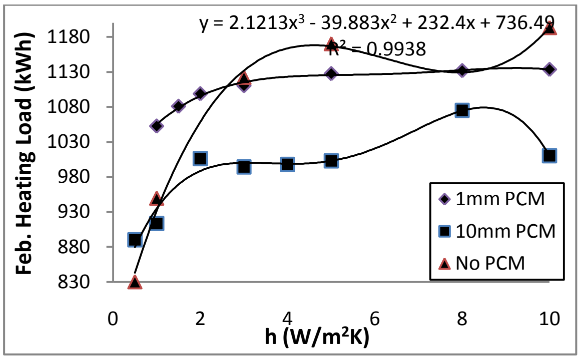

Figure 6 Effect of h on heating energy demand in the coldest month of the year, February

- and finally, annual heating load

Figure 7 illustrates annual heating load variation with h-value. The trend lines are also added to the plots. The graph shows that the sensitivity is the lowest with 1mm PCM (70745 h/m^{2}K, assuming linear trendline). Again, the maximum sensitivity goes to no PCM condition. In addition, heating load decreases with increasing the PCM amount (thickness). The curves for 1mm PCM and 10mm PCM are plynomials with power three and four, respectively.

When h < 1 W/m^{2}K (this condition is not an option in building application), no PCM condition provides the lowest energy demand in all cooling load demand and at hour 289 and in February heating energy demand.

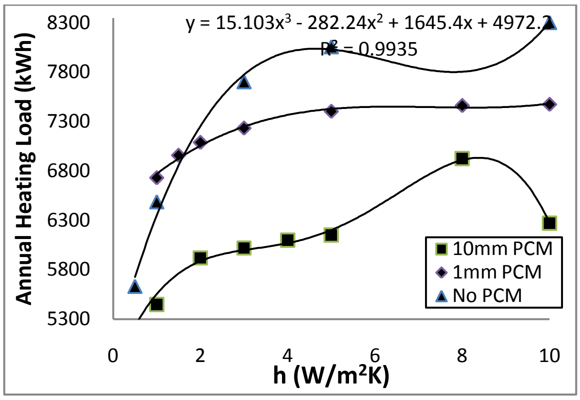

Figure 7 Effect of h on annual heating energy demand

Depending on the h-value, the operative temperature, which depends on the surface temperature of the PCM (Equation (2)), would be different at different hours of the day. Observation of the hourly operative temperatures reveals that the temperature is higher than 24℃ about 36% of the time in August. Also, the temperature is found to be less than 21℃ about 83% of the time in February (Figure 8). Generally, by increasing the h-value, deviation of the operative temperature from the set points increases. By increasing the PCM thickness: 1) the chance of the PCM surface temperature goes below 21℃ increases in February, but the chance of increasing the PCM surface temperature above 24℃ decreases in August, and 2) operating temperature is less sensitive to h-value.

SUMMARY AND DISCUSSION

Analysis of data shows that during the investigated periods, outdoor (ambient) temperature is less than 24℃ most of the time in summer (it is over 24℃ about 18% of the time) and always less than 21℃ in winter in Toronto. Therefore, increasing the h-value helps the conduction of heat (by reducing the thermal resistance of the interior surface layer) from outside to inside to balance the convection heat transfer increase. In the other words, in summer it acts in favor of comfort by decreasing the energy demand and keeping the zone temperature inside the set points (21℃ - 24℃), and in winter it acts against comfort which means more energy demand to keep the zone temperature higher than 21℃. The duration of summer is much less than that of winter in Toronto that justified the higher slope of the graph (h versus Energy Demand) in winter than in summer.

When comparison is made between no PCM and PCM condition while h is very low (0.5 W/m^2K), envelope with no PCM always demands less energy, except the annual heating load case. It is worth mentioning that the operative temperature is about 25℃ in summer and 20℃ in winter, which is one degree centigrade above and below the set points respectively.

To check the effectiveness of the PCM in different seasons, regardless of its thickness, the operative temperature is extracted from TRNSYS outputs. Recalling Equation (2), PCM surface temperature can be calculated as follows:

$$T_s = \frac{T_{op} - AT_\infty}{1 - A} \quad (4)$$

When T_{op} is above 24℃ or below 21℃, T_∞ is 24℃ or 21℃ respectively. In both cases, as Equation (4) stipulates, T_{op} is an estimator for T_s. Due to the thermal mass, by increasing the thickness of the PCM, sensitivity of the surface temperature to h-value reduces (see Figure 8). In Toronto, ambient temperature is always less than 21℃ in winter. On the other hand, this temperature is usually less than 24℃ in summer; therefore, the PCM surface temperature is less than 21℃ most of the time in winter (80%) and about 35% of the time it is above 24℃ in summer. This implies that phase transformation happens more frequently in winter than in summer. As a result, the chosen Dal HSM PCM is more effective in winter than in summer.

CONCLUSION

ASHRAE Standard 140-2001 (BESTEST), case 600, in Toronto is simulated in TRNSYS 16 incorporated with phase change material (PCM), Type 204. Two different thicknesses of PCM, one and ten millimeter, are covered on all of the wall and floor surfaces. Simulations are conducted for inside convective heat transfer coefficient (h) from 0.5 to 10 W/m^2K and the specifications of DAL HSM PCM, developed at Dalhousie University. Set points of 21℃ (heating) and 24℃ (cooling) are considered for all simulations. Generally, increasing the amount (thickness) of the PCM (layer) reduces the energy demand except for h = 0.5 W/m^2K condition, In this case, no PCM has the lowest energy demand. In summer (cooling demand), by increasing the h-value the energy demand slightly decreases (negative correlation). In winter (heating conditions), energy demand is sensitive to h-value with positive correlation in Toronto climate conditions. In addition, it is concluded that PCM brings more benefits in winter than summer in terms of saving energy.

ACKNOWLEDGEMENTS

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NONMENCLATURE

A = weighting factor

ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers

C = specific heat capacity

CFD = computational fluid dynamics

h-value = inside convective heat transfer coefficient

OT = operative temperature

PCM = phase change material

q = average convective heat transfer flux

TRNSYS 16 = simulation software version 16

T = temperature

u = air speed

Subscript

mrt = mean radiant temperature

op = operative

p = constant pressure

e = effective

s = surface

T = effective (in Type 204 module)

∞ = center of the zone

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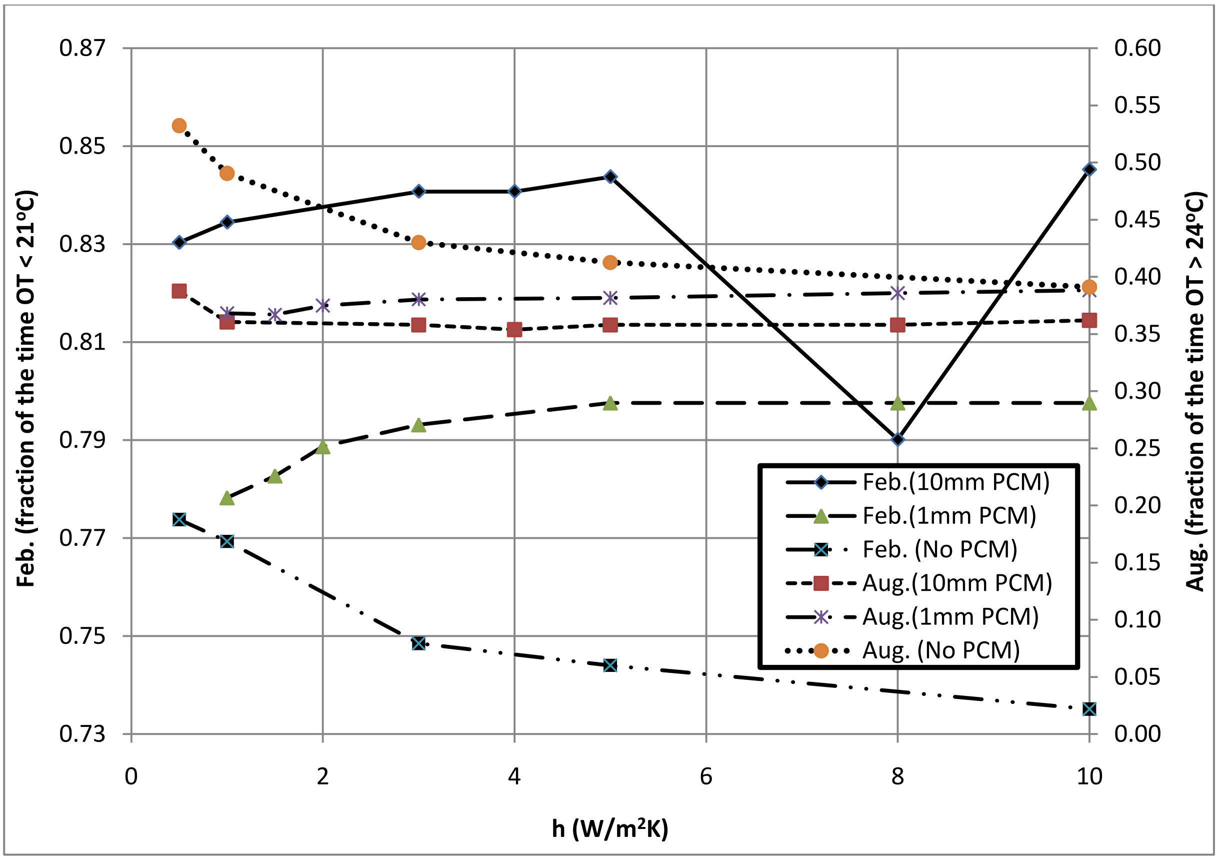

Figure 8 Effect of h-value on operative temperature (OT) (No PCM, 1mm PCM, and 10mm PCM) in August (secondary axis) and February