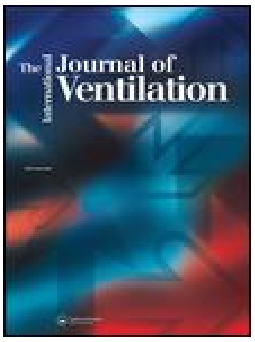

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A Novel Method for Thermostat Set Point Prediction for Energy Savings and/or Better Human Thermal Comfort - A Zonal Modelling Approach

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Abstract

Very often the set point temperature is selected to satisfy comfort requirements and/or to save energy consumption in buildings. However, the thermostat location is usually outside the occupied space and located on the wall near a front door or in a hallway that is subject to warm and cold draughts. A discrepancy exists between the temperature at the thermostat location and the occupied zones.

A zonal model has been developed and evaluated using a CFD computer program, to predict thermostat set points for energy savings and/or better human thermal comfort. Two control strategies, temperature set point and Predicted Percent Dissatisfied (PPD) set point, along with three different schemes (i.e., considering a uniform temperature distribution "Uniform-zones", using the zones of the core of the building "Core-zones", and using all the zones of the occupied space "Occupied-zones"), have been investigated through four case studies in which several construction types of a one-zone building have been considered, in order to determine the thermostat set points, heating energy demands, and thermal comfort indices (Predicted Mean Vote (PMV) and/or PPD).

Key words: zonal model, heating, ventilation and air-conditioning systems, PMV and PPD.

1. Introduction

Since the disasters and troubles caused by global warming and depletion of natural resources are increasing, researchers and designers all over the world are paying more attention to building energy savings and environment protection. In the U.S. buildings consume approximately 39% of primary energy and are responsible for approximately 38% of U.S. carbon dioxide emissions, and Heating, Ventilation, and Air Conditioning (HVAC) energy consumption is one of the major parts. In modern buildings, HVAC systems control the indoor conditions, such as temperature and humidity. Besides the judicious design of HVAC systems, and the appropriate selection of air conditioning equipment, the optimal design and efficient operation of a building control system are essential to avoid waste of energy. An ideal control system is not only able to ensure comfortable and healthy conditions for the occupants inside buildings but also to reduce energy consumption.

The indoor temperature settings during both heating and cooling seasons is a critical parameter in a control system and has significant impacts on the thermal comfort within occupied spaces and on the energy use of the HVAC systems. It is therefore important to assess the existing indoor air temperature controls within facilities to evaluate the potential for decreasing energy use and/or improving indoor thermal comfort without any substantial additional investment. There are multiple options for adjustments of the indoor temperature setting that can save heating and cooling energy, among them the adjustments of indoor temperature settings by eliminating overcooling by increasing the cooling set-point during the summer or eliminating overheating by reducing the heating set-point during the winter (Krarti, 2010). As well, the thermostat feedback temperature value cannot reflect the actual air temperature of the occupied space in a room, since the thermostat is always located on a wall, not at the centre of the room. Consequently, the temperature of the thermostat is not representative of the room temperature and a temperature difference exists between the occupied space and the position where a thermostat is located. It follows that the people in the occupied space do not feel as comfortable as reflected by the thermostat feedback temperature value. Therefore, our objective is to predict this temperature difference and its effects on the energy consumption in buildings. In this paper, the temperature difference between the occupied space and the thermostat position will be quantified, under several building construction situations, and the factors that influence the magnitude of this temperature difference will also be investigated. Additionally, a new approach is developed to determine the appropriate thermostat set point, at which less energy consumption of an air conditioning system and/or a more comfortable environment for people are achieved.

The energy usage savings for these measures can be estimated accurately only based on a dynamic zonal model, to estimate the extent of the energy savings, since adjusting only the indoor temperature settings in all instances, may actually increase the energy usage. For example, when the indoor temperature is set lower during the winter, the interior spaces may require more energy because they need to be cooled rather than heated. A similar situation can lead to an increase in the reheat energy usage for the zones with reheat systems.

As well, very often, the thermostat is located near a front door or in a hallway that is subject to warm and cold draughts. These draughts can cause the thermostat to cycle the HVAC system on and off when the rest of the building needs to be neither heated nor cooled. Another potential problem is the sun shining in a window directly on the thermostat or on the wall near it. This can mislead the thermostat into switching the heating and cooling system on and off at the improper times.

2. Description of the Model Developed

A new zonal model (Megri et al., 1996; Inard et al., 2006; Megri and Haghighat, 2007) has been developed. This model is based on both energy and mass conservation equations (Equations 1 and 2) applied to different cells (or zones) of the room. As well, the power law equation (Equation 3) is used as a substitute for the Navier-Stokes momentum equations:

$$\sum_j \dot{m}_{j\to i} = 0 \qquad (1)$$

$$\sum_j \Phi_{j\to i} + \Phi_{source} = \rho_i V_i C_p \frac{\partial T_i}{\partial t} \qquad (2)$$

$$\dot{m}_{j\to i} = \rho_{j,i} S.C_d (P_j - P_i)^n \qquad (3)$$

$$P_i = \rho_i r T_i \qquad (4)$$

$$\dot{m}_{j\to i} = \rho_{j,i} S.C_d (P_j - P_i - \frac{1}{2}(\rho_j h_j + \rho_i h_i))^n \qquad (5)$$

$$\Phi_{j\to i} = C_p (\dot{m}^+_{j\to i} T_j + \dot{m}^-_{j\to i} T_i) - \frac{\lambda S}{l}(T_j - T_i) \qquad (6)$$

Other complementary equations are needed, such as Equations 4 to 6. Equation 4 represents the ideal gas equation, and Equation 5 assumes that the mass flow rate is a function of the pressure difference across the vertical face. Additionally, Equation 5 assumes that for the horizontal faces, the hydrostatic variation of pressure is taken into account. The overall heat exchange fluxes are represented by Equation 6. Jets, plumes, and boundary layers are induced in various cells, as shown in Figure 1. The application of the airflow, determined as a function of pressure distribution using a reduced form of the Navier-Stokes equations (Bouia, 1993; Dalicieux et al., 1993; Wurtz, 1995; Gagneau et al., 1997 and Haghighat et al 2001), is obviously limited to non-driving flows (zones with relatively low velocity) in absence of thermal plumes and jets.

The new zonal model has been developed with the capability to use both types of conservation equations, “airflow” and “energy”, in the same cell. The specific conservation law is used for the part of the cell affected by thermal plumes, jets, and boundary conditions, as well as pressure distribution equations in another region (part) of the same cell (Inard, 1996; Bouia, 1998; Musy, 1999; Wurtz et al., 1999 and Haghighat et al., 2001). The balance equations describe the state of the sub-zones (or cells), and the equations of transfer describe the phenomena between two neighbouring cells through their interface.

To determine the aforementioned temperature difference between the thermostat location and the occupied zone, the zonal model developed is applied. This model is able to estimate the indoor temperature distributions rapidly compared to Computational Fluid Dynamic (CFD) models. In the zonal model, a room is subdivided into several zones. In each zone, a homogeneous temperature is assumed. In this room, the occupied space is defined as the space where people’s activities take place. More precisely, the occupied space is defined as the

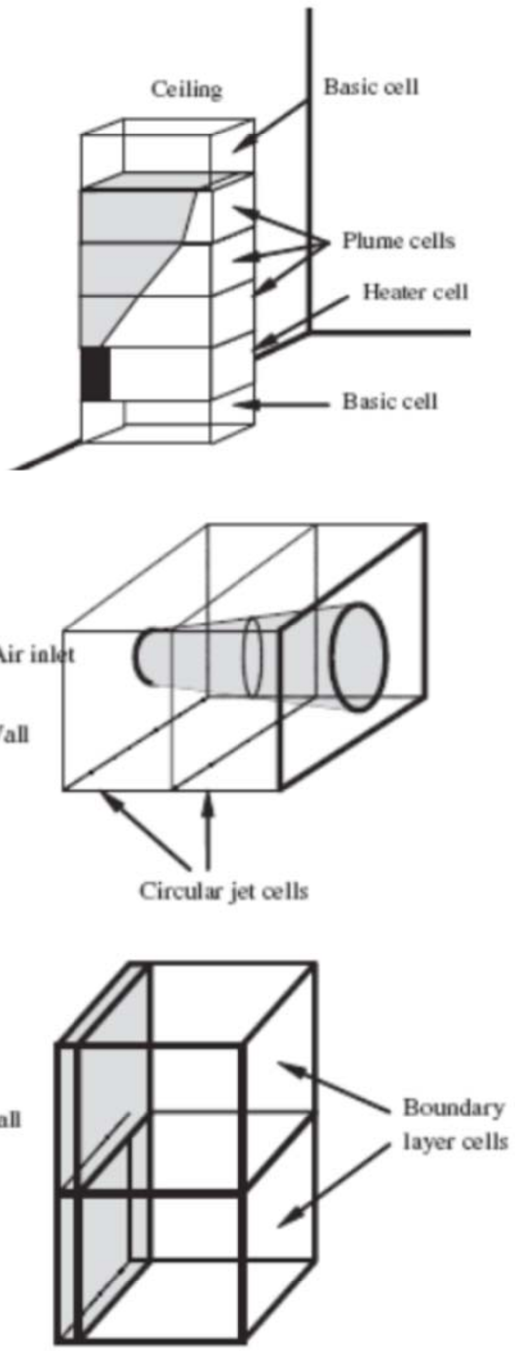

Figure 1. Jets, plumes, and boundary layers induced in various cells.

space within 1 foot of the wall while above 6 feet from the floor is out of the occupied space.

The thermostat position is located in a specific zone. The occupied space is represented by a number of indoor cells. Three schemes have been investigated: a uniform temperature distribution "Uniform-zones", the four central zones of the core of the building "Core-zones", and all the zones of the occupied space "Occupied-zones". All these schemes are utilized to define the Occupied Space Temperature (OST).

In the "Uniform-zones" scheme, the OST (defined in Equation 7) is calculated from the one-zone model, in which the homogeneous and uniform temperature distribution of the entire room space is assumed.

$$\sum h_{c,i} A_i (OST_{Uniform-zones} - T_{s,i}) = 0 \tag{7}$$

where $h_{c,i}$ (W/m^2 K) is the convective heat transfer coefficient of surface i; A_i (m^2) is the area of surface i; $T_{s,i}$ (°C) is the temperature of surface i; $OST_{Uniform-zones}$ (°C) is the OST of the "Uniform-zones" scheme.

In the "Core-zones" scheme, the average temperature of the room core four zones is regarded as the OST which is defined as:

$$OST_{Core-zones} = \sum_{1}^{N} T_{(i,j)} \;/\; N \tag{8}$$

where $T_{(i,j)}$ (°C) is the temperature of the zones located at the core of the room; and $OST_{Core-zones}$ (°C) is the OST of the "Core-zones" scheme. N is the number of the zones constituting the core of the room (we use 4 in our cases).

In the "Occupied-zones" scheme, the average temperature of the occupied space (the average of the M cells constituting the occupied space) is the OST which is defined as:

$$OST_{Occupied-zones} = (\sum T_{(i,j)}) \;/\; M \tag{9}$$

where $T_{i,j}$ (°C) is the temperature of zones constituting the entire occupied space; $OST_{Occupied-zones}$ (°C) is the OST of the "Occupied-zones" scheme; and M represents the number of the zones constituting the occupied space.

Two control strategies of the thermostat set point are considered, which are the indoor temperature and the PPD index settings. For the indoor temperature control strategy, a single temperature value, i.e. 20°C, is used as the OST. This single temperature value can also be called the Objective Temperature (OT) which represents the intended temperature value of the occupied space.

For the PPD index control strategy, a single PPD value, i.e. 6% or 15%, is used as the Objective PPD (OPPD) which represents the intended PPD value of the occupied space. The OPPD values of the three schemes, “Uniform-zones”, “Core-zones”, and “Occupied-zones”, can also be defined from Equations 7, 8, and 9, respectively, in which the PPDs are predicted instead of the temperatures. From the characteristics of the PPD index, there are two corresponding PMV index or temperature values for each single PPD index, representing contrasting climates. Consequently, a PMV or a temperature range generated by using these two values is achieved instead of a single value. Any temperature value in this range ensures that its corresponding PPD value is not larger than the predefined PPD set point (OPPD), 6 % or 15%.

The general heating system is considered in this paper, which stands for the non-specified air-conditioning system in a room or a building. The heating energy demands of a room or a building are determined by considering the heat losses from the structures. Therefore, the room temperature distributions corresponding to this type of system are only determined by natural conventions, i.e. the effects of buoyancy and gravity, and no mechanical air-conditioning system is specified. The procedure to estimate the thermostat set points (temperature values of the cell where the thermostat is located) and their corresponding energy demands are described below:

Step 1: Selection of the OT or OPPD value, and the thermostat position

The values of OT and OPPD considered in our cases are selected. Usually, the OT value selected, for economic reasons, is 20°C for the temperature control strategy. For OPPD value, 6% and 15% are usually selected for comfort and economic values for the PPD control strategy. Any zone (or cell) of the room may be a potential thermostat location. An accurate thermostat location that can reflect the actual situation contributes to improving the reliability of prediction results.

Step 2: Determination of the thermostat set point

The predefined values of the OT or OPPD in Step 1 will be approached by gradually adjusting the room set temperature of the one-zone thermal model, when the zonal model is utilized to predict the temperature or the PPD index distributions corresponding to the different schemes, “Uniform-zones”, “Core-zones”, and “Occupied-zones”. When the predefined values of the OT or OPPD are reached, the current temperature value of the zone Location (5,6) is regarded as the thermostat set point, and the temperature difference between the occupied space and the thermostat position may be determined as well.

Step 3: Computation of the heating energy demands of the building

Once the thermostat set point is determined, its corresponding room surface temperatures that were used by the zonal model to approach the OT or OPPD in Step 2 are also known. Using these surface temperatures and the energy balance equation:

$$\sum h_{c,i} A_i (T_{New\ Set\ Temperature} - T_{s,i}) = 0$$

the new set temperature $T_{New\ Set\ Temperature}$ can be predicted where $h_{c,i}$ (W/m^2) is the convective heat transfer coefficient of surface i, A_i (m^2) is the area of surface i, $T_{s,i}$ (°C) is the temperature of surface i and $T_{New\ set\ temperature}$ is considered as the corrected design temperature for the one-zone thermal model to predict the heating energy demands.

3. Case Studies

3.1 Basic Conditions

The 1st of January, Geneva, Switzerland, has been selected for the winter season simulation. Figure 2 shows the local outdoor temperatures and the solar radiation on the simulation day. A one-zone building of size 3.1 m × 3.1 m × 2.5 m, has been considered in the simulation. This zone has been divided into 60 subdivisions (6×1×10 cells) to be used by the zonal model. The zonal model divisions are shown in Figure 3. The position (5,6) in Figure 3 is considered as the typical thermostat location and is used for the determination of the temperature difference between the thermostat location and the occupied zone. In this paper, the location (5,6) is regarded as the only position for the thermostat. The temperature of the thermostat location (5,6) is the temperature of the cell (5,6) using the zonal model. The preliminary simulations show that the inside surface temperatures of the north and south walls of the building were very close, and only one zone was applied in the north-south direction (2 dimensions) in the zonal model.

For the “Core-zones” scheme, the average temperature of the room core zones, (5,3), (5,4), (6,3), and (6,4), as shown in Figure 3, is regarded as the OST which is defined as:

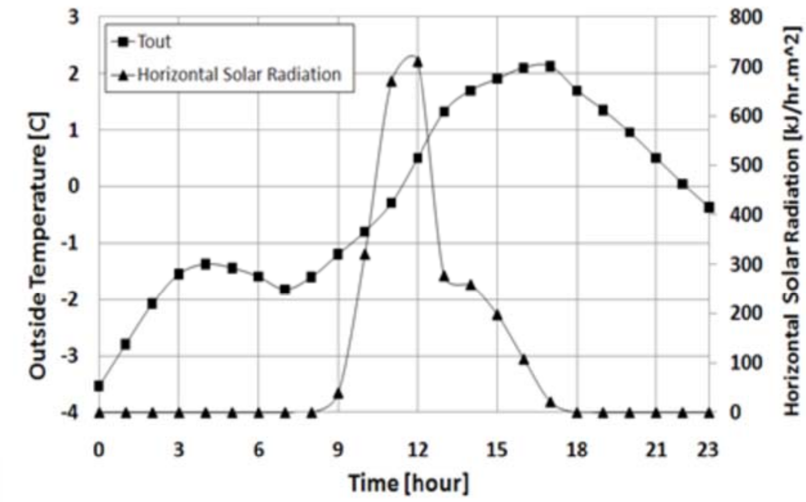

Figure 2. Outdoor temperatures and solar radiation.

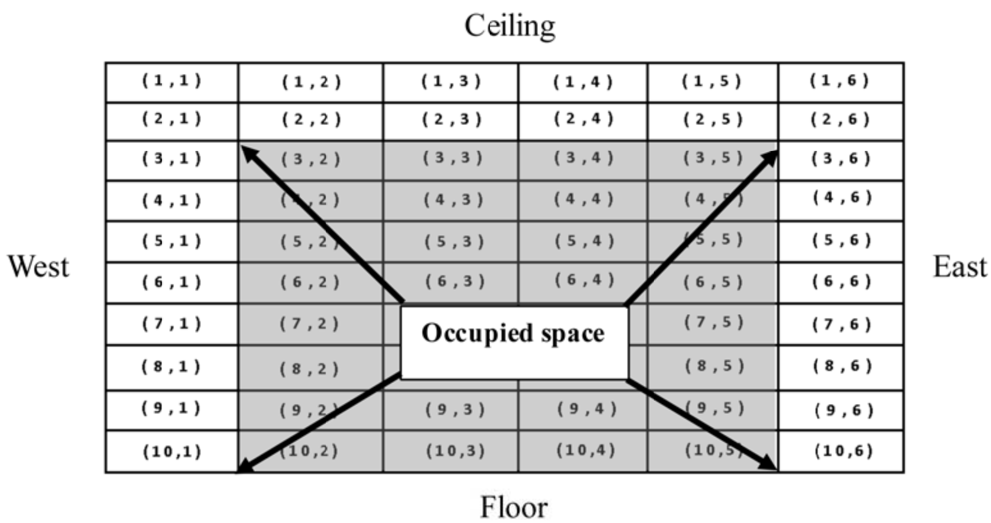

Figure 3. Zone divisions of room
(the occupied zone: the regions marked in grey).

$$OST_{Core-zones} = (T_{(5,3)} + T_{(5,4)} + T_{(6,3)} + T_{(6,4)}) / 4 \quad (10)$$

For the "Occupied-zones" scheme, the average temperature of the occupied space (or more specifically the average temperature of the 32 cells constituting the occupied space) is the OST which is defined as:

$$OST_{Occupied-zones} = (\sum T_{occupied\ space}) / 32 \quad (11)$$

In this paper, four cases considering different construction types have been studied. In cases 1 and 2, two different thermal mass constructions (light and heavy, as shown in Table 1) have been studied, while the heat transfer coefficients of these two building constructions are assumed identical. The characteristics of the four external walls, the floor area, and the roof are presented in Tables 2 and 3. The characteristics of the light thermal mass construction are regarded as the baseline. In case 3, the heat transfer coefficient of the west wall construction is reduced from 2.218 W/m^{2}K to 0.588 W/m^{2}K, representing an addition of insulation materials. Case 4 assumes a window, with an area of 3.1 m^2, the overall heat transfer coefficient (U-

Table 1. Thermal mass characteristics of building materials (ASHRAE Fundamentals, 2005).

		Heavy		Light	
	Conductivity (kJ/h m K)	Specific Heat (kJ/kg K)	Density (kg/m^3)	Specific Heat (kJ/kg K)	Density (kg/m^3)
Brick	3.2	1	2000	0.8	1600
Insulation	0.144	0.8	240	0.8	40
Concrete	7.56	0.92	3000	0.8	1360

Table 2. Characteristics of the external walls.

External Walls	Area (m^2)	U-Value (W/m^2 K)	Solar Absorptance		Convective Heat Transfer Coefficient (W/ m^2K)	
			Inside	Outside	Inside	Outside
North	7.75	0.339	0.75	0.3	4.2	17.78
South	7.75	0.339	0.75	0.3	4.2	17.78
East	7.75	0.588	0.75	0.3	4.2	17.78
West	7.75	2.218	0.75	0.3	4.2	17.78

Table 3. Characteristics of the floor and roof.

	Area (m^2)	U-Value (W/m^2 K)	Solar Absorptance		Convective Heat Transfer Coefficient (W/m^2K)	
			Inside	Outside	Inside	Outside
Floor	9.61	0.313	0.8	-	2.1	-
Roof	9.61	0.233	0.35	0.75	5.2	17.78

Table 4. Conditions used for the model validation.

	North [°C]	South [°C]	East [°C]	West [°C]	Ceiling [°C]	Floor [°C]	West Window [°C]
Cases 1 and 2	20.60	20.57	20.01	15.97	20.88	20.90	-
Case 3	20.23	20.20	19.65	19.65	20.51	20.54	-
Case 4	21.02	20.99	20.41	16.20	21.29	21.31	8.01

value) of 5.68 W/m^2K, and the solar heat gain coefficient SHGC (g-value) of 0.855 on the west wall. An ideal internal shading device is used, which is assumed to be able to block 100% of the solar radiation. In other words, no solar radiation can go into the room through this window.

These four cases aim to predict the thermostat set points and heating energy demands of different temperature and PPD control strategies and schemes (“Uniform-zones”, “Core-zones”, and “Occupied-zones”), in consideration of different construction types. In these four cases, the infiltrations and the internal heat gains have been ignored. A seated man wearing trousers and a long-sleeved shirt has been assumed in the thermal comfort PMV/PPD predictions. The PMV and PPD are the human thermal comfort indices, which are used to predict people’s steady-state comfort responses within a space (ASHRAE Fundamentals, 2005).

The model developed has been evaluated and compared to the prediction of a CFD model (PHOENICS computer program). The validations in terms of temperature and energy consumption were performed. Table 4 displays the boundary conditions (surface temperatures) for these validations.

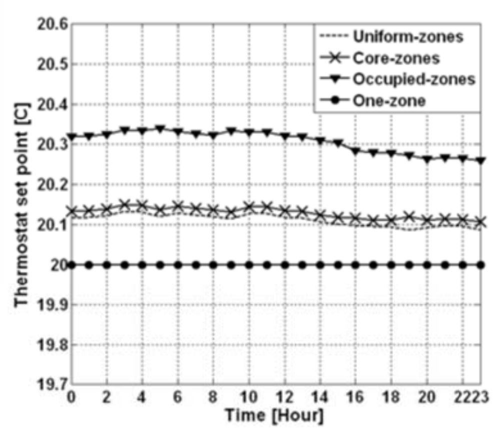

Figure 4. (a) Thermostat set points of the temperature control strategy.

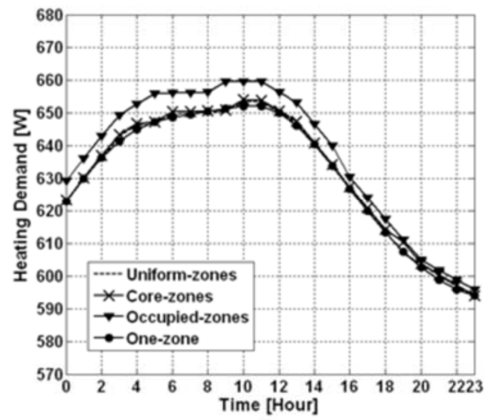

Figure 4. (b) Heating energy demands of the temperature control strategy.

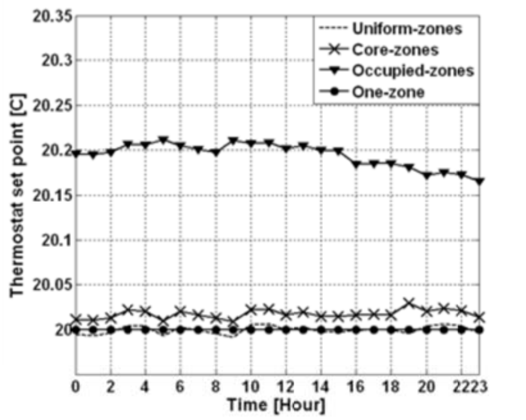

Figure 5. Corrected design temperatures of the temperature control strategy.

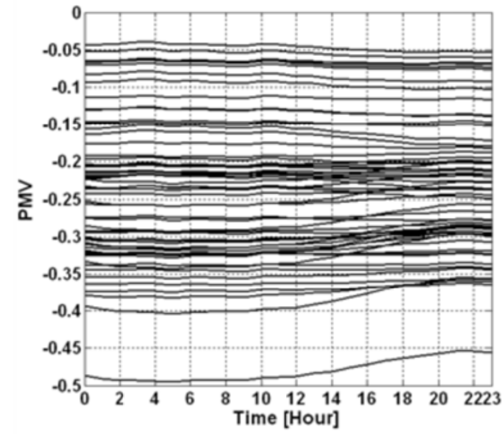

Figure 6a. PMVs for "Uniform-zones" scheme of the temperature control.

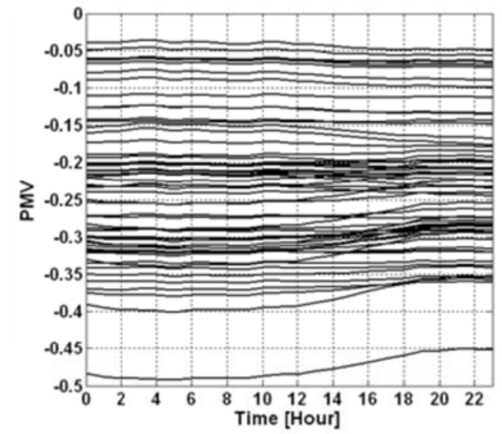

Figure 6b. PMVs for "Core-zones" scheme of the temperature control strategy.

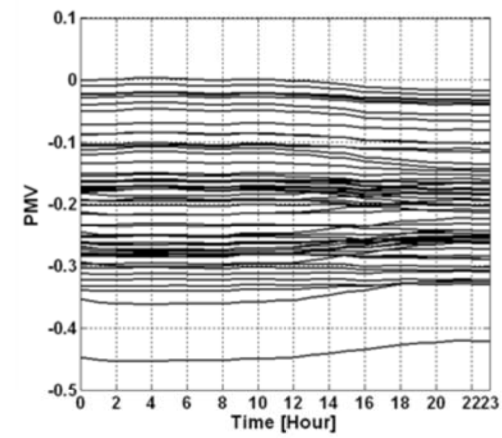

Figure 6c. PMVs for "Occupied-zones" scheme of the temperature control strategy.

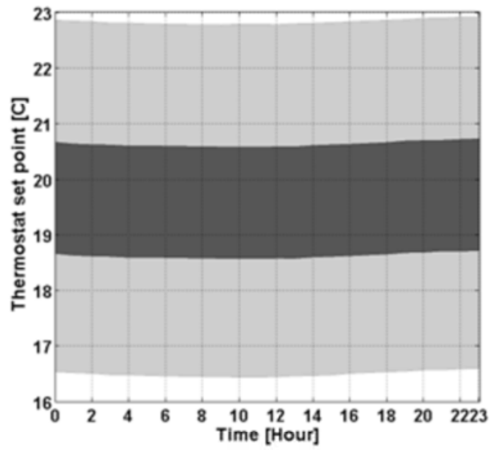

Figure 7a. Thermostat set point ranges for "Uniform-zones" scheme of the PPD control strategy.

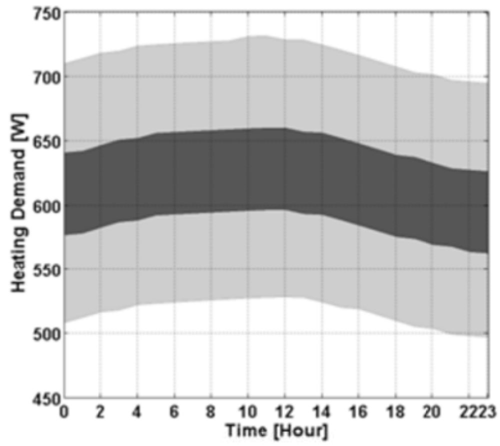

Figure 7b. Heating energy demand ranges for "Uniform-zones" scheme of the PPD control strategy.

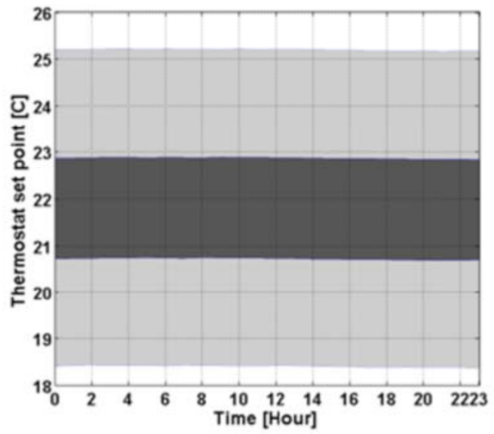

Figure 7c. Thermostat set point ranges for "Core-zones" scheme of the PPD control strategy.

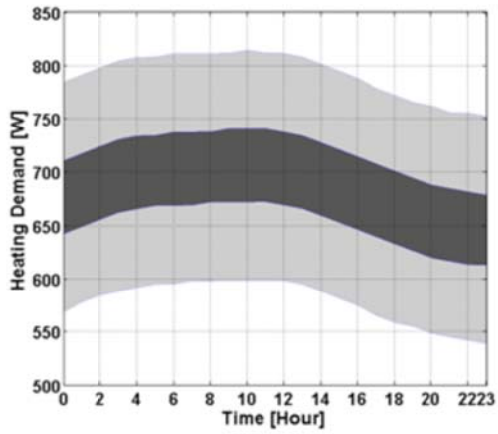

Figure 7d. Heating energy demand ranges for "Core-zones" scheme of the PPD control strategy.

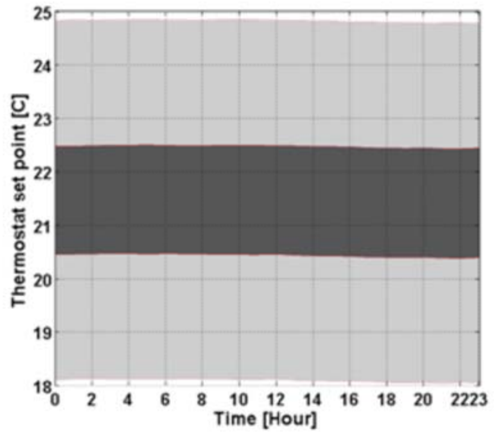

Figure 7e. Thermostat set point ranges for "Occupied-zones" scheme of the PPD control strategy.

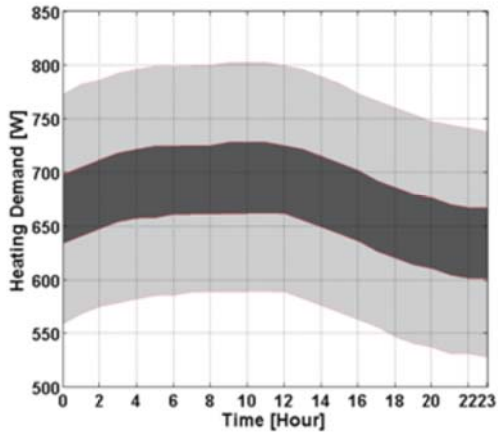

Figure 7f. Heating energy demand ranges for "Occupied-zones" scheme of the PPD control strategy.

3.2 Case 1 (Light Construction) Result

The thermostat set points of the different schemes ("Uniform-zones", "Core-zones", and "Occupied-zones") are displayed in Figure 4a, when the temperature control strategy is applied. Figure 4b displays the heating energy demands of these different schemes, and Figure 5 shows the corresponding corrected design temperatures that are used to predict the heating demands. In these three figures, the "One-zone" represents the result of the traditional one-zone thermal model. Figures 6a, 6b, and 6c display the zonal PMV profiles of these three schemes, "Uniform-zones", "Core-zones", and "Occupied-zones", respectively. The new design temperature is not very different from the original one, since we are considering only a general heating system, where the room temperature distributions corresponding to this type of system are only determined by natural convection.

Figures 7a, 7c, and 7e display the thermostat set point ranges of the different schemes, "Uniform-zones", "Core-zones", and "Occupied-zones", respectively, when the PPD control strategy is applied. In these figures related to the PPD control strategy, the grey and black shades represent the results of the OPPD values, 6% and 15%, respectively. Additionally, their corresponding heating energy demand ranges are shown in Figures 7b, 7d, and 7f.

3.3 Case 2 (Heavy Construction) Result

The validation results corresponding to cases 1 and 2 are shown in Figures 8a and 8b, demonstrating the comparisons of temperature distribution between the zonal model developed and the CFD program PHOENICS. Figures 8a and 8b display the comparison for cases 1 and 2. As shown in these figures, good agreements are observed.

The thermostat set points of the different schemes ("Uniform-zones", "Core-zones", and "Occupied-zones") are displayed in Figure 9a, when the temperature control strategy is applied. Figure 9b displays the heating energy demands of these different schemes, and Figure 10 shows the corresponding corrected design temperatures. Figures 11a, 11b, and 11c display the zonal PMV profiles of these three schemes, "Uniform-zones", "Core-zones", and "Occupied-zones", respectively.

Figures 12a, 12c, and 12e display the thermostat set point ranges of the different schemes, "Uniform-zones", "Core-zones", and "Occupied-zones", respectively, when the PPD control strategy is applied. Additionally, their corresponding heating energy demand ranges are shown in Figures 12b, 12d, and 12f. The new design temperature is not very different from the original one, since we are considering only a general heating system, where the room temperature distributions corresponding to

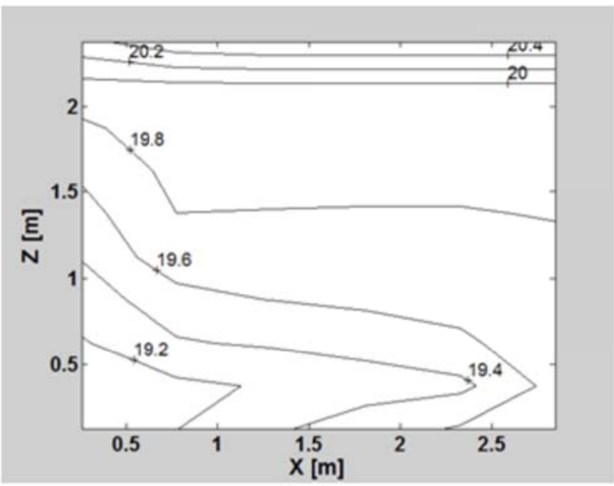

Figure 8a. Temperature distribution (°C) of Case 1 using zonal model (6×1×10).

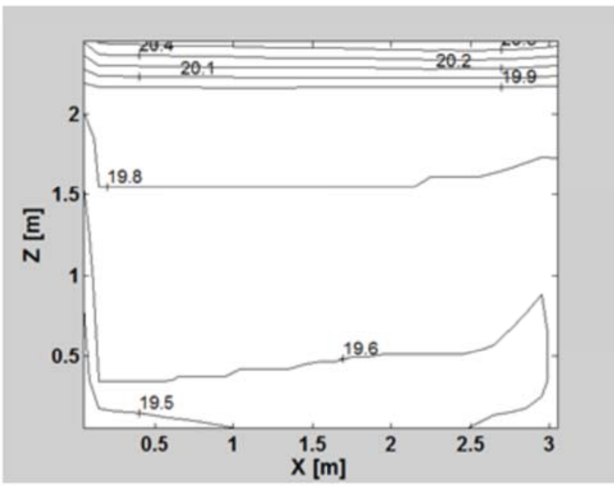

Figure 8b. Temperature distribution (°C) of Case 1 using the CFD program PHOENICS (31×20×25).

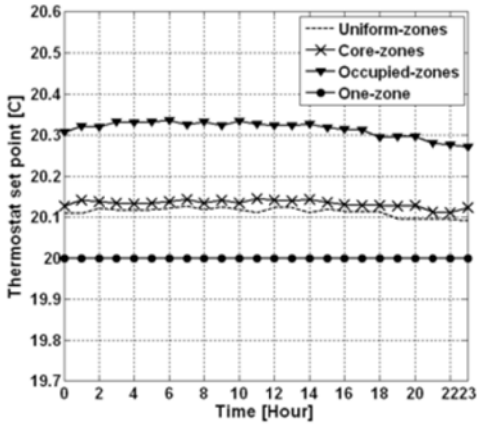

Figure 9a. Thermostat set points of the temperature control strategy.

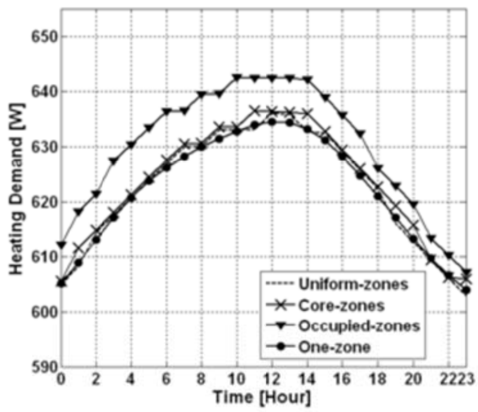

Figure 9b. Heating energy demands of the temperature control strategy.

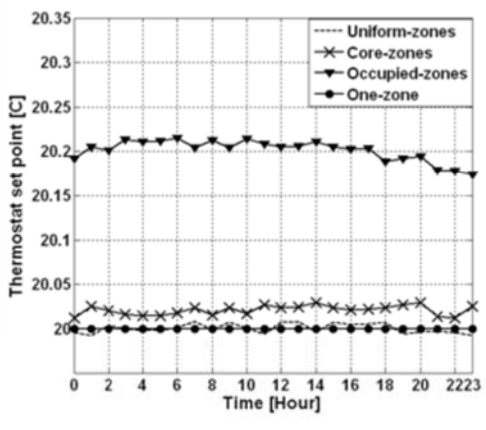

Figure 10. Corrected design temperatures of the temperature control strategy.

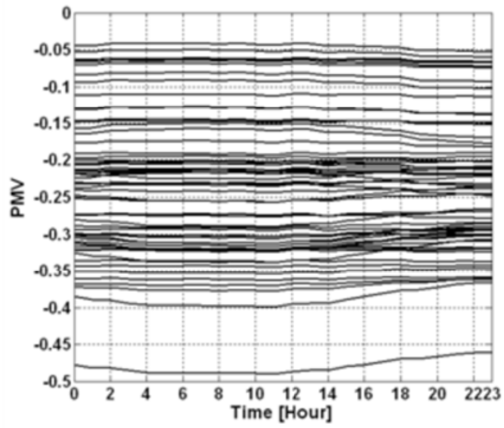

Figure 11a. PMVs for "Uniform-zones" scheme of the temperature control.

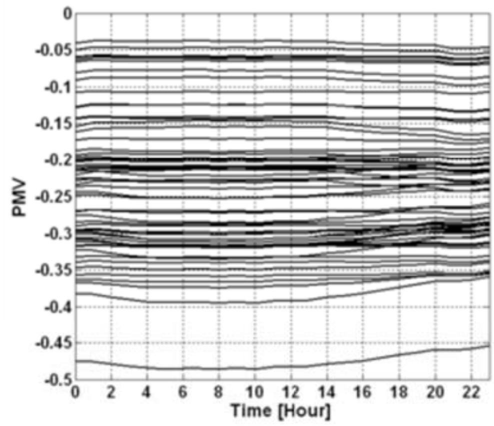

Figure 11b. PMVs for "Core-zones" scheme of the temperature control strategy.

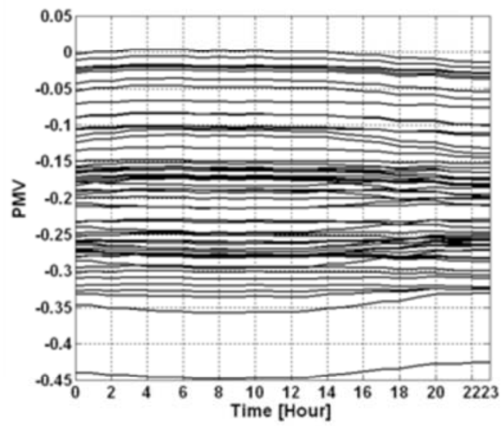

Figure 11c. PMVs for "Occupied-zones" scheme of the temperature control strategy.

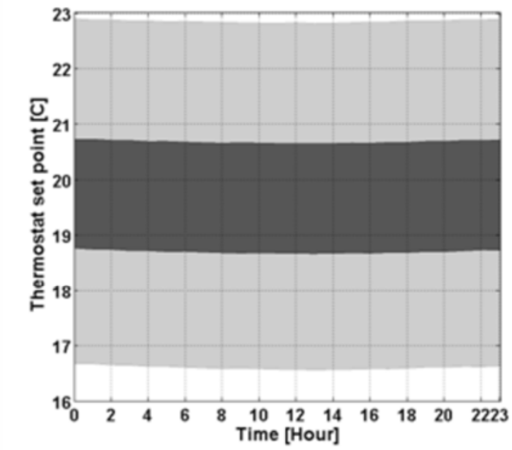

Figure 12a. Thermostat set point ranges for "Uniform-zones" scheme of the PPD control strategy.

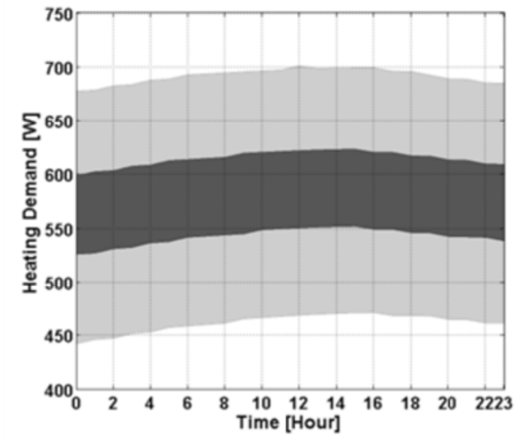

Figure 12b. Heating energy demand ranges for "Uniform-zones" scheme of the PPD control.

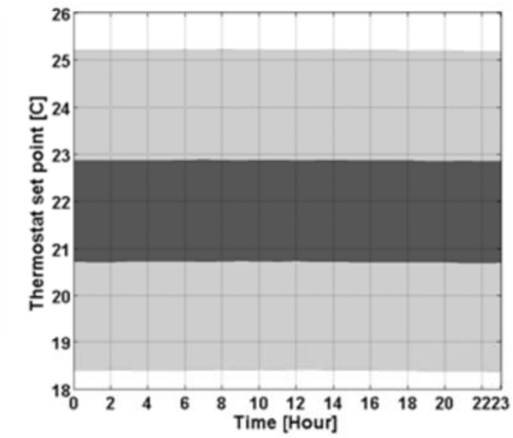

Figure 12c. Thermostat set point ranges for "Core-zones" scheme of the PPD control strategy.

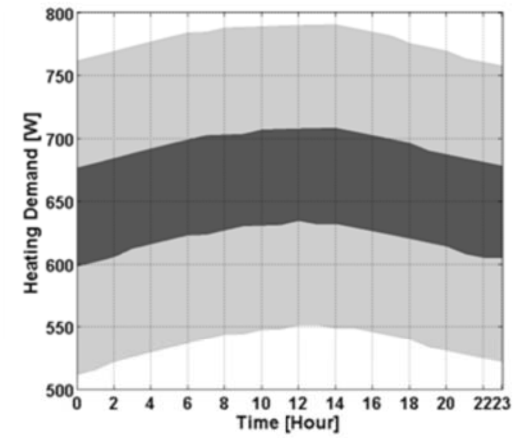

Figure 12d. Heating energy demand ranges for "Core-zones" scheme of the PPD control strategy.

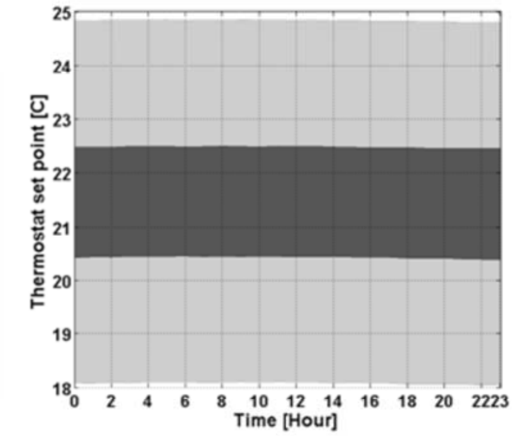

Figure 12e. Thermostat set point ranges for "Occupied-zones" scheme of the PPD control strategy.

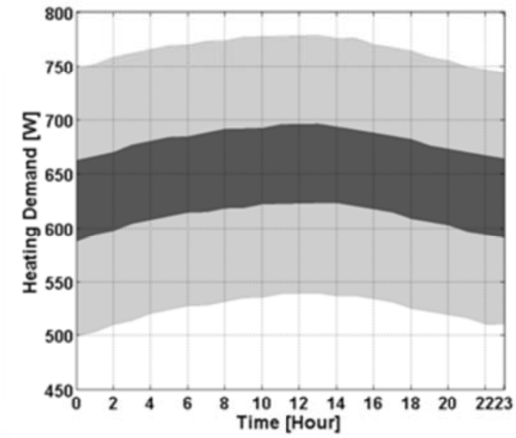

Figure 12f. Heating energy demand ranges for "Occupied-zones" scheme of the PPD control strategy.

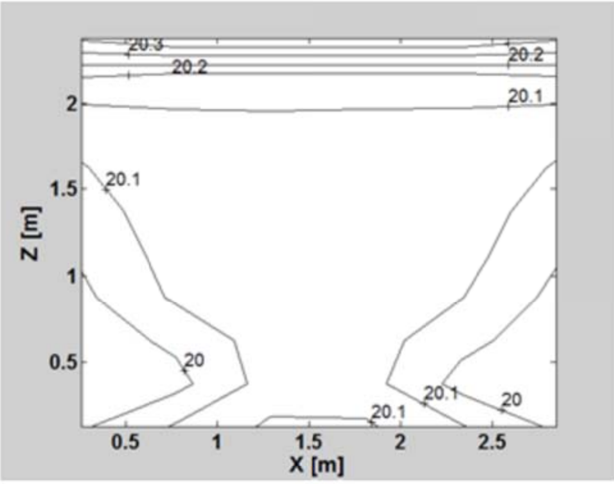

Figure 13a. Temperature distribution (°C) of Case 3 using zonal model (6×1×10).

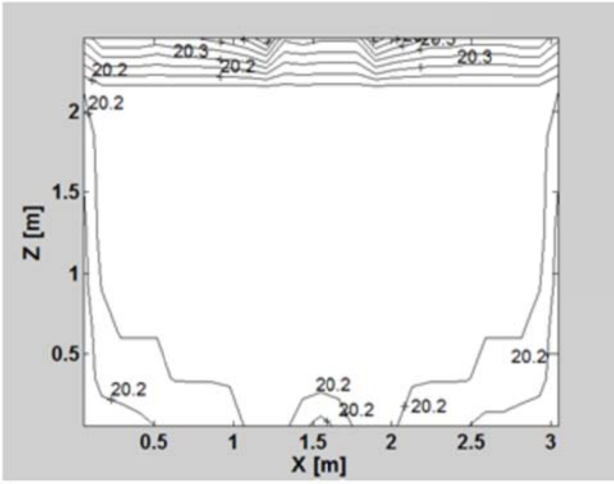

Figure 13b. Temperature distribution (°C) of Case 3 using CFD program PHOENICS (27×27×25).

this type of system are only determined by natural convection.

3.4 Case 3 (West Wall Addition of Insulation Materials) Result

The validation results corresponding to case 3 are shown in Figures 13a and 13b, demonstrating the comparisons of temperature distribution between the zonal model developed and the CFD program PHOENICS. Figures 13a and 13b display the comparison for case 3. As shown in these figures, good agreements are observed.

The thermostat set points of the different schemes ("Uniform-zones", "Core-zones", and "Occupied-zones") are displayed in Figure 14a, when the temperature control strategy is applied. Figure 14b displays the heating energy demands of these different schemes, and Figure 15 shows the

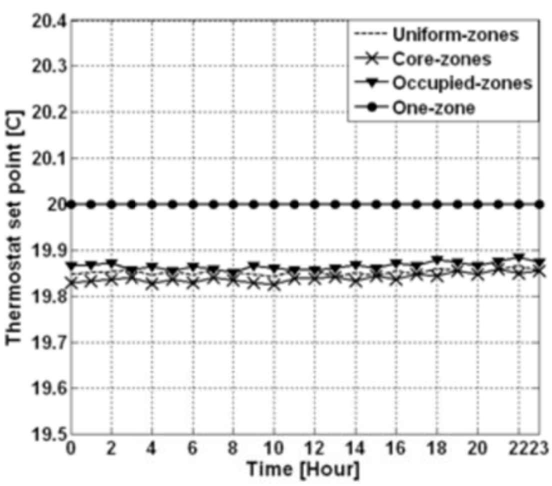

Figure 14a. Thermostat set points of the temperature control strategy.

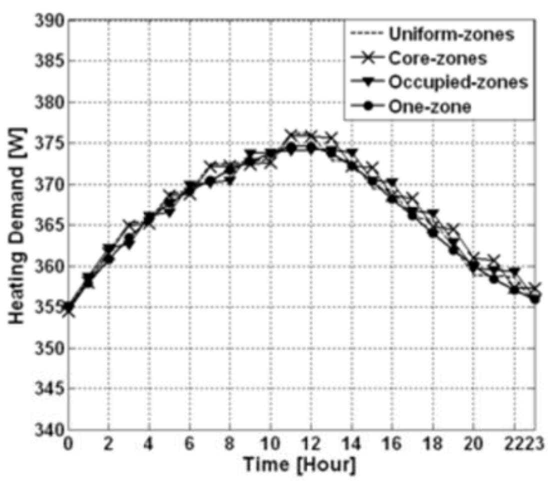

Figure 14b. Heating energy demands of the temperature control strategy.

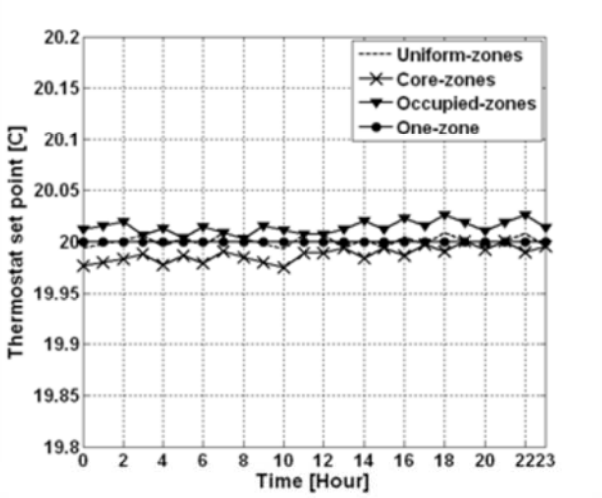

Figure 15. Corrected design temperatures of the temperature control strategy.

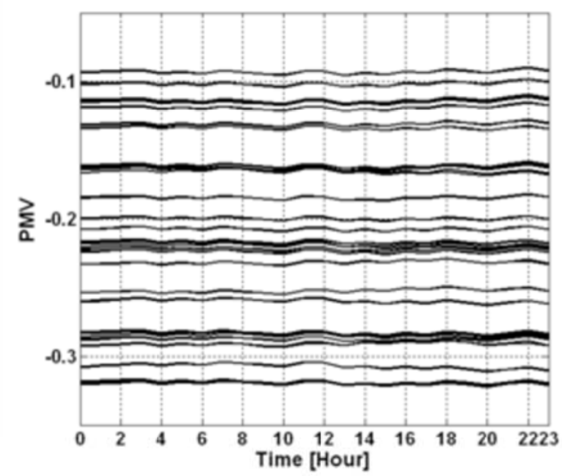

Figure 16a. PMVs for "Uniform-zones" scheme of the temperature control strategy.

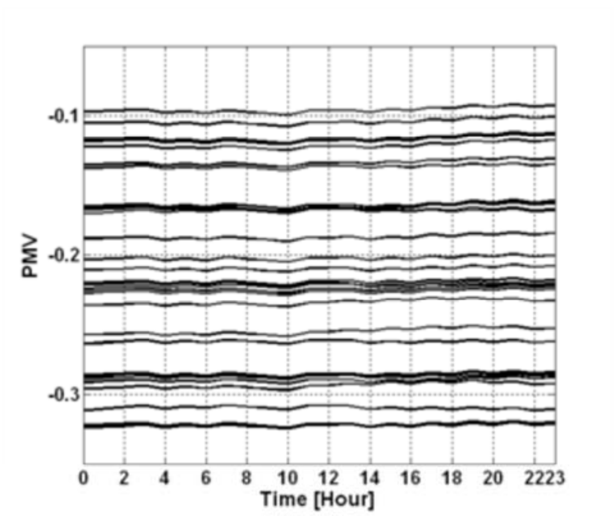

Figure 16b. PMVs for "Core-zones" scheme of the temperature control strategy.

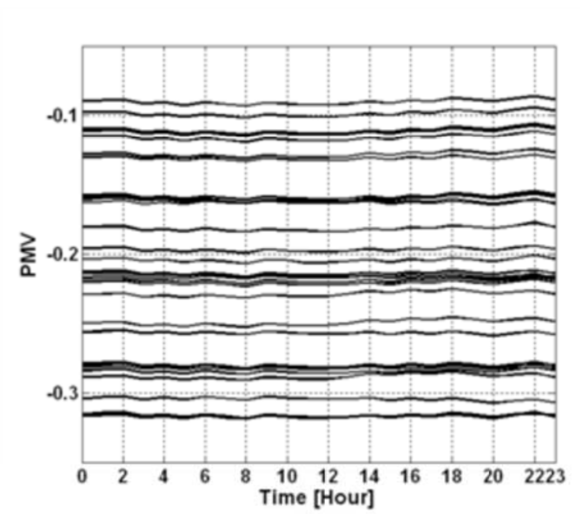

Figure 16c. PMVs for "Occupied-zones" scheme of the temperature control strategy.

corresponding corrected design temperatures. Figures 16a, 16b, and 16c display the zonal PMV profiles of these three schemes, "Uniform-zones", "Core-zones", and "Occupied-zones", respectively.

Figures 17a, 17c, and 17e display the thermostat set point ranges of the different schemes, "Uniform-zones", "Core-zones", and "Occupied-zones", respectively, when the PPD control strategy is applied. Additionally, their corresponding heating energy demand ranges are shown in Figures 17b, 17d, and 17f.

3.5 Case 4 (Window at the West Wall) Result

The validation results corresponding to case 4 are shown in Figures 18a and 18b, demonstrating the comparisons of temperature distribution between the zonal model developed and the CFD program PHOENICS. Figures 18a and 18b display the comparison for case 4. As shown in these figures, good agreements are observed.

The thermostat location (5,6) temperature is a crucial parameter, which directly impacts the results

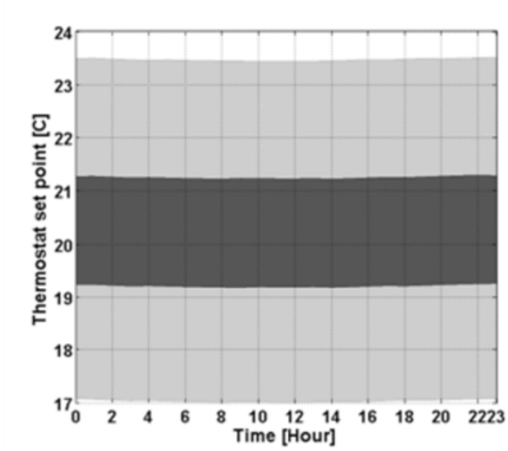

Figure 17a. Thermostat set point ranges for "Uniform-zones" scheme of the PPD control strategy.

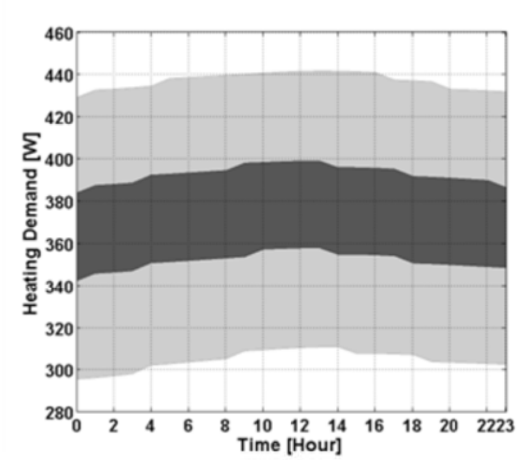

Figure 17b. Heating energy demand ranges for "Uniform-zones" scheme of the PPD control strategy.

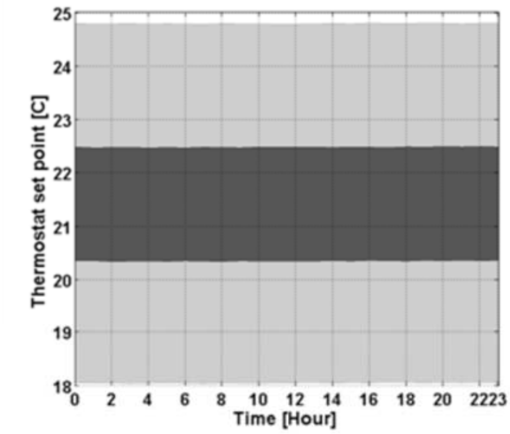

Figure 17c. Thermostat set point ranges for "Core-zones" scheme of the PPD control strategy.

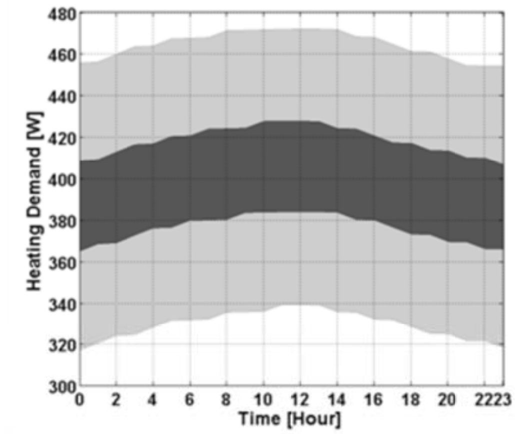

Figure 17d. Heating energy demand ranges for "Core-zones" scheme of the PPD control strategy.

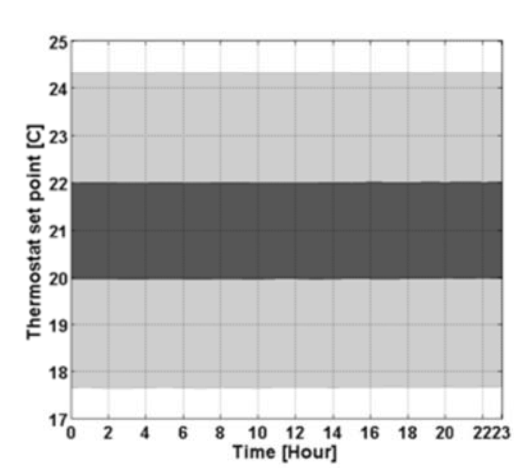

Figure 17e. Thermostat set point ranges for "Occupied-zones" scheme of the PPD control strategy.

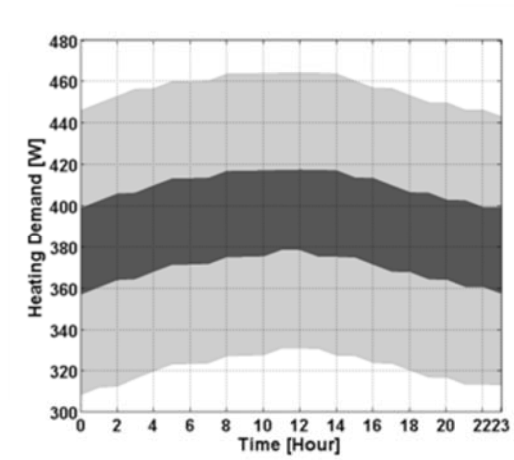

Figure 17f. Heating energy demand ranges for "Occupied-zones" scheme of the PPD control strategy.

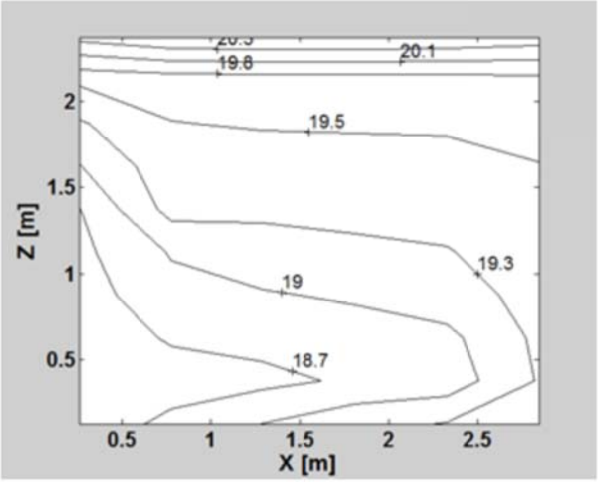

Figure 18a. Temperature distribution (°C) of Case 4 using zonal model (6×1×10).

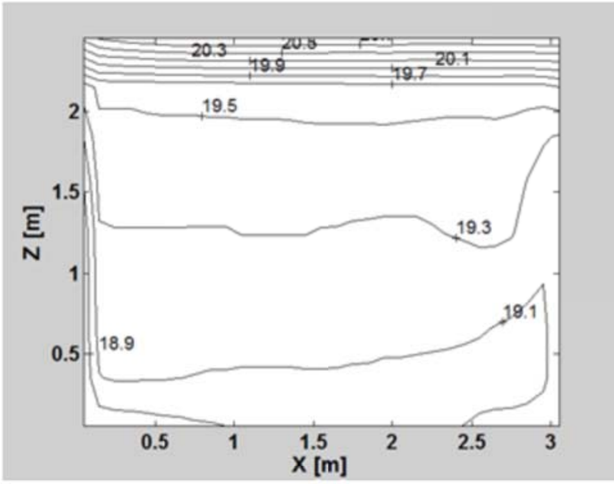

Figure 18b. Temperature distribution (°C) of Case 4 using the CFD program PHOENICS (31×20×30).

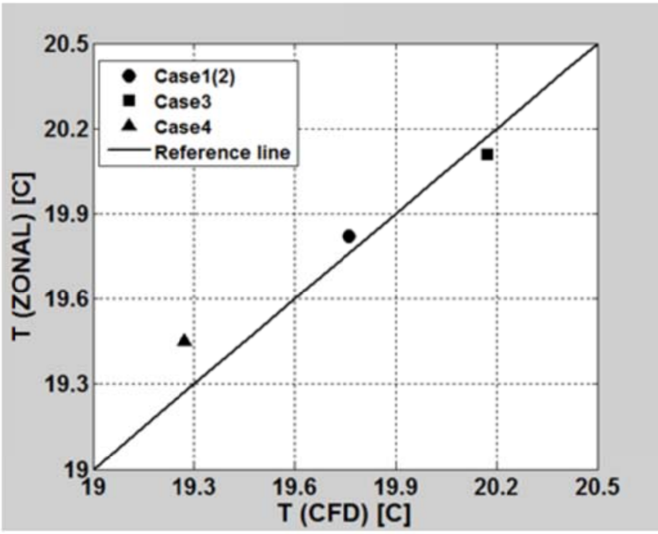

Figure 19. Zonal vs. CFD thermostat location temperatures (°C) of different cases.

in terms of predicted thermostat set point. Therefore, whether or not the zonal model is able to estimate the thermostat location temperature accurately is significantly important. Figure 19 displays the thermostat location temperature comparison between the zonal and CFD models for all cases. From these results, it seems that the zonal model is able to predict the thermostat location temperature in a very good agreement with the CFD model.

The thermostat set points of the different schemes (“Uniform-zones”, “Core-zones”, and “Occupied-zones”) are displayed in Figure 20a, when the temperature control strategy is applied. Figure 20b displays the heating energy demands of these different schemes, and Figure 21 shows the corresponding corrected design temperatures. Figures 22a, 22b, and 22c display the zonal PMV profiles of these three schemes, “Uniform-zones”, “Core-zones”, and “Occupied-zones”, respectively.

Figures 23a, 23c, and 23e display the thermostat set point ranges of the different schemes, “Uniform-zones”, “Core-zones”, and “Occupied-zones”, respectively, when the PPD control strategy is applied. Additionally, their corresponding heating energy demand ranges are shown in Figures 23b, 23d, and 23f.

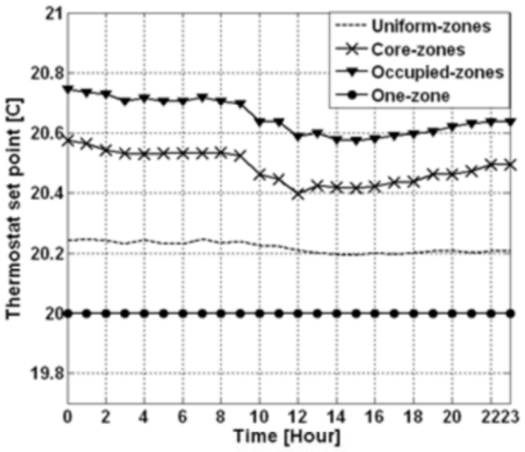

Figure 20a. Thermostat set points of the temperature control strategy.

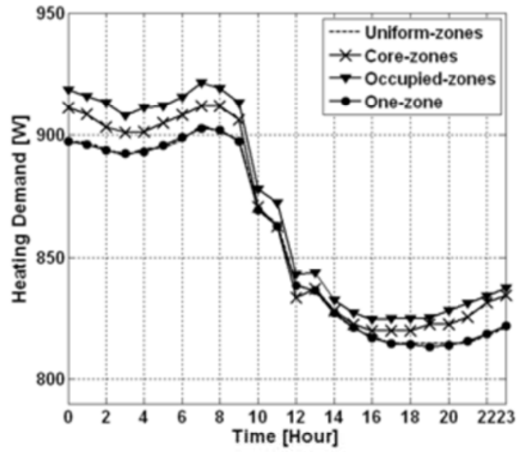

Figure 20b. Heating energy demands of the temperature control strategy.

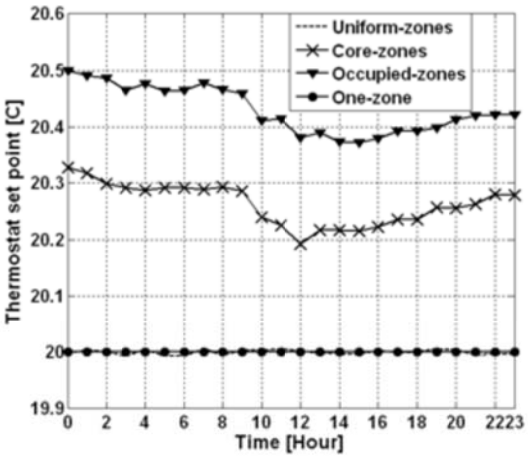

Figure 21. Corrected design temperatures of the temperature control strategy.

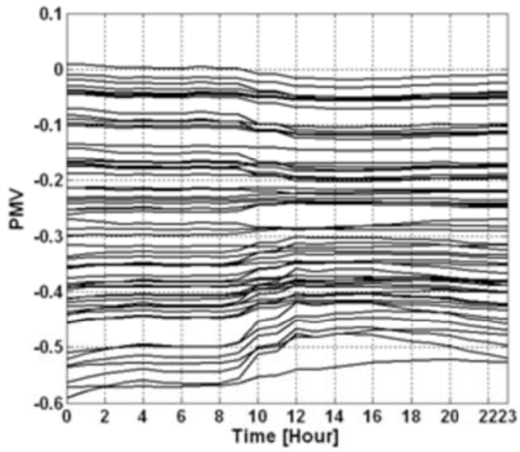

Figure 22a. PMVs for "Uniform-zones" scheme of the temperature control.

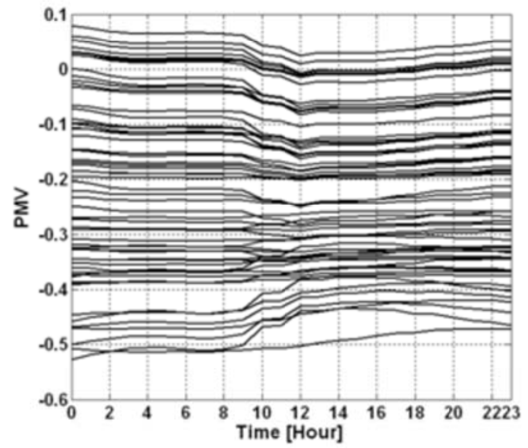

Figure 22b. PMVs for "Core-zones" scheme of the temperature control.

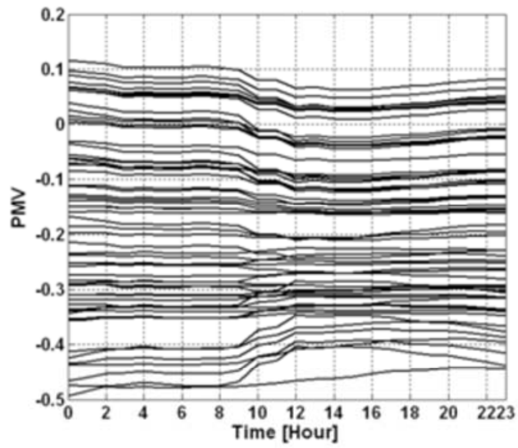

Figure 22c. PMVs for "Occupied-zones" scheme of the temperature control.

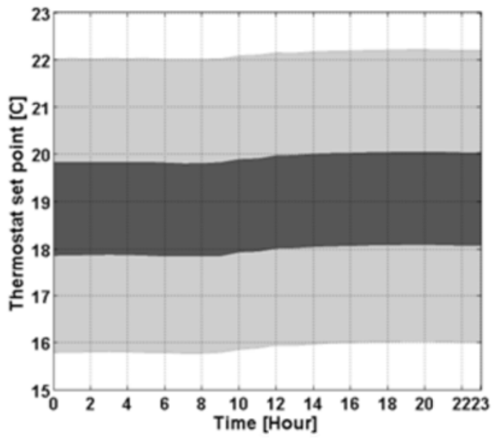

Figure 23a. Thermostat set point ranges for "Uniform-zones" scheme of the PPD control strategy.

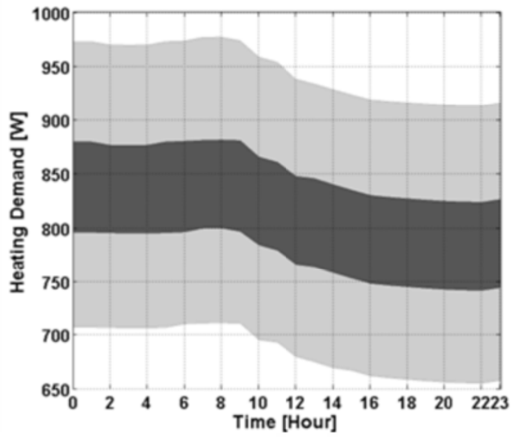

Figure 23b. Heating energy demand ranges for "Uniform-zones" scheme of the PPD control strategy.

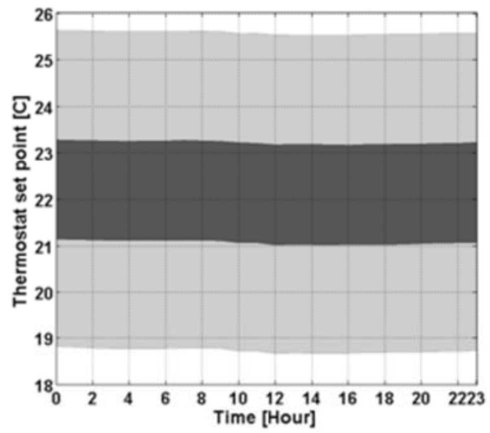

Figure 23c. Thermostat set point ranges for "Core-zones" scheme of the PPD control strategy.

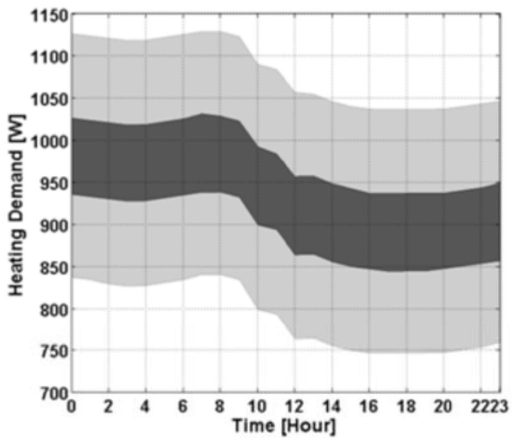

Figure 23d. Heating energy demand ranges for "Core-zones" scheme of the PPD control strategy.

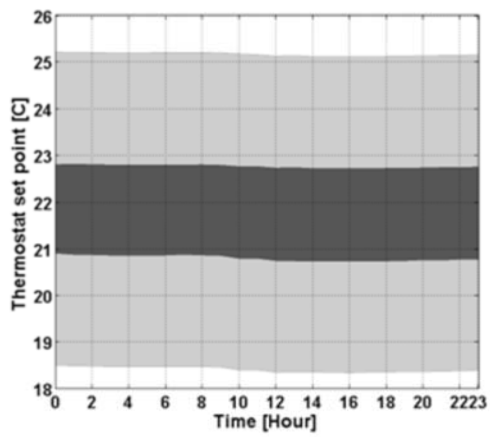

Figure 23e. Thermostat set point ranges for "Occupied-zones" scheme of the PPD control strategy.

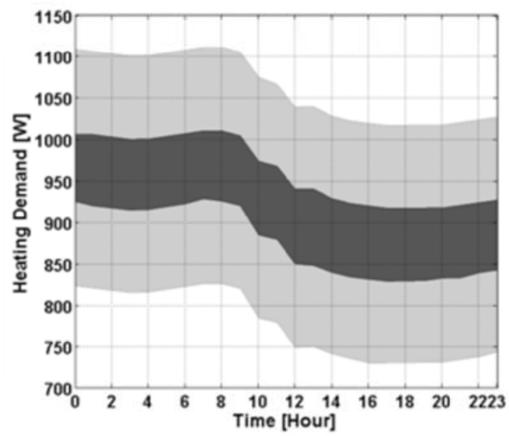

Figure 23f. Heating energy demand ranges for "Occupied-zones" scheme of the PPD control strategy.

3.6 Discussion

As shown in Figures 4a, 9a, 14a, and 20a, the different OST schemes account for the different thermostat set point profiles. In the traditional one-zone model, constant set point temperatures are utilized, and there is no difference between the thermostat set point and the OT, as shown in Figures 24a, 24b, 24c, and 24d, which display the temperature differences between the OTs (various OST schemes) and the thermostat set points (defined as the temperature at location (5,6)) of = cases 1, 2, 3, and 4, respectively. In these figures, there is no significant difference observed between the results of the "Uniform-zones" and "Core-zones" schemes, except for case 4, in which a relatively non-uniform temperature distribution is observed due to the presence of a window on the west wall. A more uniform temperature distribution exists in case 3, which results in the insignificant temperature differences when the "Uniform-zones", "Core-zones", and "Occupied-zones" schemes are applied, as shown in Figure 24c. The more non-uniform the room temperature distribution is, the larger the temperature difference that exists between the thermostat set point and the OT. No evident discrepancy is noticed in Figures 24a and 24b. Consequently, whether the thermal mass of the building construction is light or heavy does not significantly affect the thermostat design temperature and the inside temperature distribution, as long as the heat transfer coefficients of the building construction

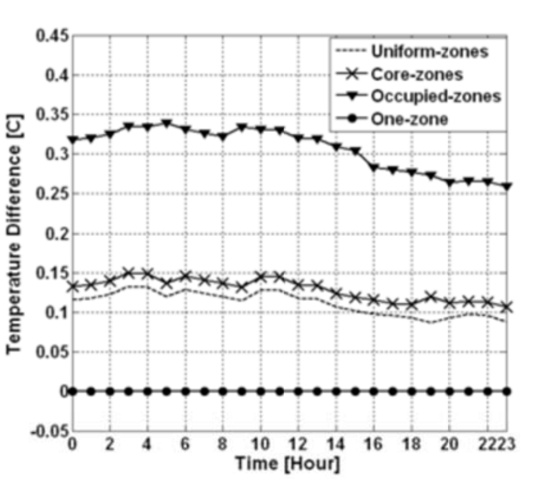

Figure 24a. Temperature differences between the thermostat set points and the OTs of Case 1.

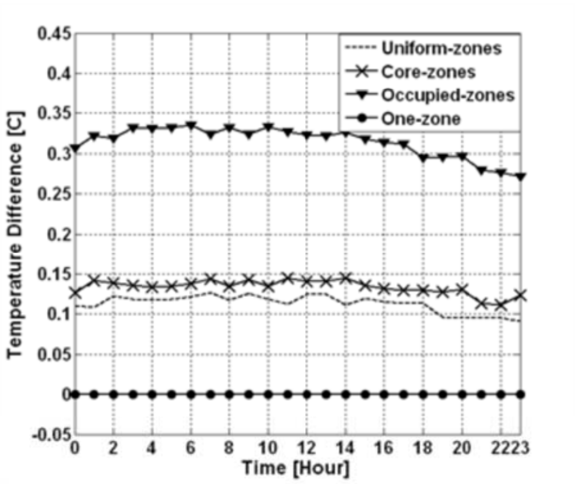

Figure 24b. Temperature differences between the thermostat set points and the OTs of Case 2.

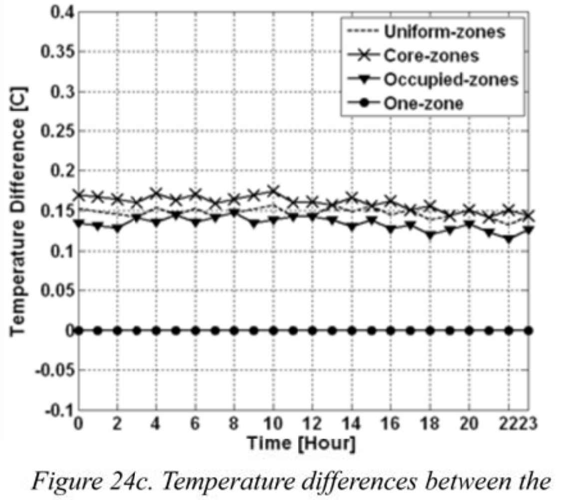

Figure 24c. Temperature differences between the thermostat set points and the OTs of Case 3.

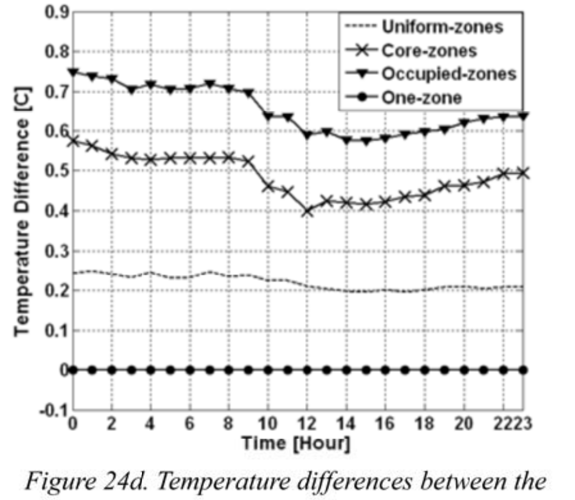

Figure 24d. Temperature differences between the thermostat set points and the OTs of Case 4.

at the surface level are the same. However, these two thermal masses indeed account for different energy demands, as shown in Figures 4b and 9b. A lower energy is required when the heavy thermal mass of the building construction is applied.

The "Occupied-zones" scheme, as the strictest requirement for indoor thermal comfort among these three schemes, requires higher thermostat set point temperatures and more energy, as shown in Figures 4a, 9a, 14a, and 20a, as well as Figures 4b, 9b, 14b, and 20b. Nevertheless, noticeable improvements of indoor thermal comfort level are observed from Figures 6a, 6b, and 6c for case 1, Figures 11a, 11b, and 11c for case 2, and Figures 22a, 22b, and 22c for case 4, when the "Occupied-zones" OST scheme is used. No obvious difference is found from Figures 16a, 16b, and 16c for case 3, owing to its nearly uniform temperature distribution within the room. After the comparison of the PMVs for both "Uniform-zones" and "Core-zones" schemes of these four cases, one may conclude that an improvement of the PMVs for the "Core-zones" scheme over the "Uniform-zones" one is only observed in case 4. Therefore, the difference between these two schemes in terms of thermal comfort and energy consumption can only be distinguished when a significantly non-uniform temperature distribution exists within a room.

In fact, whether the room air temperature distribution is uniform or not plays a key role in the predictions of room thermostat set point and energy demand. For a room characterized by a nearly uniform temperature distribution, the default design parameters of the traditional one-zone model, such as the design air temperature 20ºC, are still good to use, because of the small discrepancy between the three OST schemes and the one-zone model in terms of the thermostat set point, energy demand, and corrected design temperature, as shown in Figures 14a, 14b, and 15. On the other hand, for a room characterized by a significantly non-uniform temperature distribution, these default design parameters of the traditional one-zone model, i.e. the design air temperature, are not acceptable; instead, a corrected design temperature, as shown in Figure 21, is needed, in order to improve the design accuracy of the one-zone model.

Besides the temperature control strategy, the results of the PPD strategy are also displayed. In these results, significant differences are observed, when the different OPPD values, 6% and 15%, are used. The differences of the results between the "Core-zones" and "Occupied-zones" schemes, in terms of thermostat set point (Figures 7c, 7e, 12c, 12e, 17c, 17e, 23c and 23e) and energy demand (Figures 7d, 7f, 12d, 12f, 17d, 17f, 23d, and 23f) are negligible, compared to the results of the "Uniform-zones" scheme.

4. Conclusions

Two control strategies, temperature and PPD, along with three different schemes, "Uniform-zones", "Core-zones", and "Occupied-zones", have been investigated through four case studies, in which two construction types of a one-zone building have been considered, in order to determine the thermostat set points, heating energy demands, and thermal comfort indices (PMV and/or PPD).

After the comparisons and results analysis, we conclude that:

- For a space with a nearly uniform temperature distribution, such as the interior space of a building, the default design parameters of the traditional one-zone model, i.e. 20ºC for the design air temperature, are still acceptable to use in the energy demand estimations and even in the determinations of the thermostat set points when the building is under operation. However, for a space with a significantly non-uniform temperature distribution, such as the space that has exterior walls within a building, the corrected design temperatures for the one-zone model are needed in the estimations of energy demand, and for operation purposes of the building the thermostat set points need to be updated by using the values obtained.
- The existence of the difference between the OST and the thermostat-position temperature is proved. This difference increases, when the temperature distribution becomes non-uniform.
- In the temperature control strategy, the "Occupied-zones" scheme gives a more comfortable environment, compared to the other two schemes, but requires more energy consumption. In the PPD strategy, either the "Core-zones" or "Occupied-zones" scheme is recommended, if the thermal comfort of a building is a big concern. In comparison to the temperature control strategy, the PPD method is more flexible and feasible to use for operation purposes of a building, since, instead of a single thermostat set point value, a range is used in this

strategy, which gives the Building Management System (BMS) more options concerning either the energy consumption or indoor thermal comfort, or even both.

- Although the construction thermal mass does not significantly influence the indoor temperature distribution of a building it changes the structure of energy consumption, according to the results shown.

The information, such as the thermostat set point temperatures determined by using either the temperature or PPD strategy or other similar approaches, can be obtained at the design stage through pre-simulations considering different factors that can affect the indoor air temperature distributions, such as outdoor weather conditions, thermostat locations, the characteristics of HVAC system diffusers, or even people's activities. The results from these pre-simulations may be used as a database in the BMS of a building. The BMS may compute the appropriate set point for every room space, based on the room thermostat feedback and the information included in the database. This set point is able not only to maintain a desirable comfort level in the occupied space, but also to optimize the energy consumption, as designed at the design stage. The more factors considered in the pre-simulations, the more accurate results from the BMS are achieved.

Nomenclature

C_d	discharge coefficient, (ms^{-1} Pa^{-n})
C_p^o	heat capacity of air, (J kg^{-1} $°C^{-1}$)
h_i	height of airflow element *i*, (m)
l	distance between node *i* to *j*, (kg s^{-1})
$\dot{m}_{j\to i}$	airflow rate from cell *j* to *i*, (kg s^{-1})
n	airflow model exponent, (dimensionless)
P_i	pressure in cell *i*, (Pa)
S	surface area, (m^2)
t	time, (s)
T_i	air temperature in cell *i*, (°C)
V_i	volume of cell *i*, (m^3)

Greek Symbols

λ	conductivity of air, (W m^{-1} $°C^{-1}$)
ρ_i	density of air in cell *i*, (kg m^{-3})
$\rho_{i,j}$	air density depending on Sign ($\dot{m}_{j\to i}$), (kg·m^{-3})
$\Phi_{j\to i}$	heat flux from cell *j* to *i*, (W)
Φ_{Source}	heat source in cell *i*, (W)

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