The 6th IBPSA Canada Conference
La 6e conférence d'IBPSA – Canada
Winnipeg, May 19 – 20

QUANTIFYING THE EFFECTS OF ZONED COOLING SYSTEMS ON HOUSEHOLD PEAK ELECTRICITY DEMAND

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ABSTRACT

In this study, the potential benefits of a zoned cooling system during peak summer days are examined through the use of a building energy simulation model. The model presents a means for evaluating various cooling control strategies to quantify the effects of a zoned system on the reduction and shifting of household peak electricity demand. The development and theoretical basis of the model are summarized. Simulations were carried out on a model representative of the (CCHT) Canadian Centre for Housing Technology houses. Results for selected control strategies are presented for a hot, humid and sunny peak summer day in Southern Ontario. The simulation results suggest that a gradual thermostat set-point increase during the peak cooling period may be ineffective if the system is undersized for peak summer conditions. The use of external shades was shown to significantly reduce the sensible cooling load allowing an otherwise undersized system to fully meet the cooling demand. Such a passive measure would likely increase the effectiveness of the zoned cooling control strategies examined.

INTRODUCTION

Most two-story residential dwellings in Canada employ a single thermostat for heating and cooling control. Such a rudimentary control strategy often results in unbalanced delivery of heating and cooling and is ill-equipped to cope with stratification between levels. Heating/cooling systems equipped with a zoned air-handler and distributed thermostats present a viable, commercially available alternative to remedy such problems for both new construction and retrofit applications.

From a homeowner perspective, the clear benefit of zoned systems is the flexibility in controlling the comfort zone of each designated living space. Potential energy savings can also be realized by applying thermostat setback control to individual zones, thus reducing the overall space heating/cooling demand. From the perspective of electrical utilities, a zoned system provides the opportunity for peak reduction strategies on hot and humid summer days, when peak electricity demand largely coincides with increased demand for space cooling.

This study describes a building energy simulation model developed to quantify the potential peak electricity demand reduction associated with the use of a zoned air conditioning system in combination with various thermostat control strategies.

The simulation model for the zoned air conditioning system is an upgrade of the model for unitary split air conditioning described in (Haddad 2004a). This model is implemented outside of the ESP-r plant domain and is intended to be used in conjunction with the ideal zone temperature controller. The predicted cooling load for the time step is used to set the Part-Load Ratio of the equipment. This PLR is then used to predict the part load degradation of the COP using an appropriate correlation. The steady-state total cooling capacity and COP at ARI rating conditions are corrected at each time step, using appropriate correlations, for the effect of the inlet wet-bulb temperature to the evaporator coil, the ambient dry-bulb temperature, and the flow rate over the indoor coil. The cooling coil Bypass Factor is corrected for the flow rate. In this model the effect of the dry cold air from the cooling coil on the space moisture balance is taken into account every time step.

The previous empirical model was validated using steady state (Neymark and Judkoff 2002, Haddad 2004a) and transient (Neymark and Judkoff 2004, Haddad 2004b) cooling test cases. In these test cases predictions from air conditioning models from various well recognized building energy analysis tools are documented to form a set of reference results. Results for the transient test cases from ESP-r were compared against the reference results with very good agreement.

METHODOLOGY

The results generated in the present study are obtained using a simulation model for the Canadian Centre for Housing Technology (CCHT) test house shown in Figure 1. This house is built to the R2000 standard

with several of its characteristics listed in Table 1. Internal sensible heat gains to the first floor zone from occupants, lighting, refrigerator, stove, dishwasher, and other kitchen appliances add up to 5.3 kWh/day with peaks in the morning, and evening. For the second floor the internal sensible heat gains from occupants, lighting, and clothes washer and dryer add up to 4.3 kWh/day.

The simulated occupancy is for two adults and two children with a total latent internal heat gain for the first and second floors of 0.47 and 0.66 kWh/day, respectively. The latent heat gain from the stove is assumed to be 40% of its total heat at 0.66 kWh/day.

Table 1: CCHT house characteristics.

Liveable Area	210 m^2 (2260 ft^2), 2 storeys
Insulation	Attic: RSI 8.6, Walls: RSI 3.5, Rim joists: RSI 3.5
Basement	Poured concrete, full basement Floor: Concrete slab, no insulation Walls: RSI 3.5 in a framed wall.
Exposed floor over the garage	RSI 4.4 with heated/cooled plenum air space between insulation and sub-floor.
Windows	Low-e coated, argon filled windows. Area: 35.0 m^2 (377 ft^2) total, 16.2 m^2 (174 ft^2) South Facing
Airtightness	1.5 air changes per hour @ 50 Pa (1.0 lb/ft^2)

Inter-zone air flow and infiltration were resolved by means of a pressure driven mass flow network. ESP-r's flow network solver is coupled to the zone thermal balance, thus capturing the interaction between air flow changes and their influence on the conditioned space. The theoretical basis of flow network modeling in ESP-r is well documented (e.g., Hensen 1991, Beausoleil-Morrison 2000, Hand 2008).

Infiltration is modeled in the explicit flow network by imposing a set of wind driven pressure coefficients on external boundary nodes and coupling the boundary nodes to internal zone nodes through a flow restriction component on each external wall in each zone. In order to tune the air leakage characteristics of the CCHT model, the Alberta Infiltration Model (AIM-2) was used as a reference to adjust the flow network crack sizes until the desired air leakage characteristics were observed. Details of the AIM-2 model can be found in (Walker and Wilson 1990).

Inter-zone air flow due to mechanical ventilation is modeled by means of constant volume flow components placed between the upper, main and basement nodes. The house air flow balance depends on the individual zone thermostat call states which determine the supply fractions to each zone. Figure 2 shows whole house ventilation balances for three possible zone cooling states: 1) both upper and main zones require cooling, 2) upper zone cooling only and 3) main zone cooling only. It is assumed that the basement does not require cooling. The return air duct is assumed to be a common duct, with return fractions set to 0.6, 0.3 and 0.1 from the basement, main level and upper level, respectively. The basement entrance as well as the stairwell between the main and upper zones are assumed to be open at all times. The actual flow rates are calculated as the product of the central circulation fan flow rate and the flow fractions. It is assumed that the mechanical ventilation is balanced such that the house is not positively or negatively pressurized. The impact of net pressurization of the indoor space on infiltration is outside the scope of this study.

Inter zone air flow can also occur due to buoyancy forces when the circulation fan and air conditioner are turned off. The highest flow rates are likely to occur between the upper and main zones under a condition of reverse thermal stratification, that is, when the upper level is cooler than the main level. In this instance, the cold air will tend to fall down the stairwell while the warmer air from the main zone will rise up the ceiling. The result is a net mixing effect taken into account in the model by imposing a mixing rate between the upper and main zones.

The original ESP-r air-conditioning model is based on the use of an ideal zone temperature controller. This type of controller does not predict the on-off behaviour of the equipment but predicts the fraction of the time step the equipment has to operate in order to meet the cooling load. This choice of controller is acceptable for predicting the energy consumption of the system, but is not acceptable for predicting peak electricity demand of the air-conditioning system. For the present study dealing with the zoned system, the ESP-r air-conditioning model was modified to use an on-off controller instead of the ideal controller. The use of the on-off controller in combination with a time constant correction factor eliminates the need for using the equipment Part-Load Ratio. The air-conditioning model was also modified to allow for variable supply and return fractions and variable flow rates as a function of the number of zones requiring cooling at any time step.

In order to balance inter zone air flows, supply and return flows are explicitly defined in the air flow network. The supply and return flows are modeled through 'known boundary' nodes and constant volume flow components. In the absence of supply/return

flows, the inter zone flows between the upper, main and basement levels would negatively or positively pressurize the conditioned space, depending on the cooling state. Such a network would lead to unrealistic infiltration rates. The supply/return flows ensure that the mechanical ventilation flows are balanced throughout the house and that all flow paths shown in Figure 2 are accounted for. The temperature and humidity ratio of the make up air fraction (~20%) entering the system is accounted for directly in the cooling coil thermodynamic balance in the air-conditioning model.

Given the large south facing glazing area of the CCHT house, it is likely that on a hot summer day the occupants would make use of interior shades to avoid direct exposure to solar radiation. Hence, the south facing windows in the model are equipped with an interior venetian blind, making use of ESP-r complex fenestration construction facility. The blinds are light in colour and the slats are closed. The reader is referred to (Lomanowski 2008) for a theoretical basis of modeling shading devices through the use of ESP-r's complex fenestration constructions.

SIMULATION

The air conditioning model represents a system composed of a central air handling unit with circulation fan and cooling coil located in the basement and a compressor/condenser fan unit located outdoors. Table 2 lists the specifications for a 2 ton (7033 W) unit used in the model.

If the system includes a zoned air handler, the circulation fan flow rate depends on the number of zones calling for cooling. The fan settings are assumed to be: 800 ft^3/min for cooling all three zones, 640 ft^3/min for two zones and one zone. Since the basement does not require cooling, the flow rate for the zoned system is 640 ft^3/min regardless of whether the main or the upper zones or both are calling for cooling. In a non-zoned system, the air handler operates at a constant flow rate of 800 ft^3/min. It is assumed that the circulation fan operates in tandem with the compressor, and is otherwise off.

Table 2: Air conditioner specifications.

Rated Capacity[1]	7033 [W]
Rated COP[1]	3.43 (SEER 13)
Max. flow rate	800 [ft^3/min]
Max. circulation fan power	300 [W]
Condenser fan power	150 [W]
Sensible Heat Ratio[1]	0.76

[1]at ARI rating conditions (26.7°C T_{dry_bulb}, 19.4°C T_{wet_bulb})

A simulation period of 24 hours with 5 start up days was used. Weather data for the 24 hour period corresponds to a hot, humid and sunny peak day on August 31, 2000 in Toronto (Figure 3). The preceding start up day is also hot, humid and sunny.

Two benchmark scenarios serve as the basis for comparison:

- B1: non-zoned cooling system with one thermostat located on the main level and a constant set-point of 23°C.
- B2: zoned cooling system with three thermostats, one on each level and a constant set-point of 23°C.

Three control strategies were selected for comparison. These constitute only a small subset of possible control strategies which are adaptable to different occupancy profiles. The resulting simulation cases are based on the zoned system in scenario B2 plus the added thermostat control strategy:

- C1: Occupants are away during the morning and early afternoon.
- C2: Occupants are at home, occupying the main level during the daytime.
- C3: Occupants are at home, occupying the second level during the daytime.

Figure 4 shows the control schedule for each scenario.

Two levels of control were considered: 1) 2°C increase in thermostat set-point and 2) cooling supply is turned off to the zone under control. The second level of control provides a means to assess the maximum impact of zoning control while the first level would likely be the minimum control action.

RESULTS

Figure 5 compares hourly temperatures of the main and upper zones as well as the hourly averaged power consumption by the cooling system (the sum of compressor, circulation fan and condenser fan power) for cases B1 and B2. Figure 6 compares the hourly temperatures and hourly averaged power consumption for the control scenarios C1, C2 and C3 relative to the reference case B1. Results are presented for the two levels of control: a) 2°C thermostat set-point increase and b) zone cooling supply off.

ANALYSIS

It is informative to first examine the cooling load profiles prior to an analysis of cooling system

performance. The cooling load curves shown in Figure 7 were generated by running a simulation with idealized cooling control, which is independent of any mechanical system specification. Inter-zone air flow is not taken into account in this approach but the results are informative none the less. The internal venetian blinds on the south have been removed to highlight the magnitudes of transmitted solar radiation. Since the windows are double glazed with a high solar heat gain coefficient (SHGC), the solar transmission represents the majority (about 85%) of the solar heat gain into the space. It is clear from Figure 7 that the cooling load is dominated by the solar gain in both zones and that the upper level constitutes about 65% of the total peak cooling load. The solar gain on the upper level is twice as large due to the larger south facing glazing area. The contribution of internal gains to the cooling load profile is evident in the morning (8:00-9:00 hrs) and evening (18:00-21:00 hrs). Although not shown in the figure, the addition of light internal venetian blinds with closed slats reduces the peak cooling load by about 15%.

Cooling System Performance: Zoned vs. Non-Zoned

The zone temperature profiles (Figure 5) indicate the state of operation of the cooling system. Sudden jumps in temperature correspond to the system turning on and off. For the benchmark cases B1 and B2, the smooth temperature curves in the afternoon hours indicate that the cooling system is on continuously. During these hours, the hourly averaged power equals the continuous power consumption of the sum of the compressor, condenser fan and circulation fan. During off-peak hours when the system is cycling on and off, the hourly averaged power is less than the peak power consumption as the equipment is running intermittently.

A comparison of the benchmark cases B1 and B2 (Figure 5) reveals that the zoned cooling system maintains the air temperature within the set-point temperature band for both the upper and main level while the non-zoned system, with thermostat located on the main level, leads to temperature stratification. The temperature difference is most pronounced at night-time when cooling is not required on the main level. Comparing the hourly averaged power profiles for these cases (Figure 5), it is evident that the zoned system supplies cooling to the upper level at night-time whereas the non-zoned system is off between 1:00-8:00 hrs and 23:00-24:00 hrs. The slight decrease in the peak hourly averaged power consumption of the zoned system is due to the difference in circulation fan flow-rates between the zoned and standard air handler.

Cooling System Performance: Control Strategies

The power profiles for control strategies C1 and C2 with a 2°C set-point increase (Figure 6.a) show only a slight reduction during the peak afternoon hours, relative to B1. This can be explained by considering that during the afternoon peak hours of case B1 and B2, the system is not able to meet the entire sensible load of the conditioned zones, as indicated by the continuous operation of the cooling system. Thus, a 2°C increment is largely ineffective during the peak afternoon hours since the cooling system may still be unable to satisfy the reduced sensible load. The reduced sensible load remains greater than the sensible cooling capacity, resulting in continuous cooling system operation.

Control strategy C3 with a 2°C set-point increase (Figure 6.a) results in a greater reduction in cooling power in the late afternoon hours. This is attributed to the difference between cooling load fractions on the upper and main level and the cooling supply fractions. The sensible cooling load on the upper level accounts for about 65% of the total sensible cooling load whereas the supply fractions are evenly split. The 2°C set-point increase on the main level allows the main level to float more so than with the original set-point. As a result, all of the cooling capacity is supplied to the upper zone more often. Since the available capacity now exceeds the cooling load on the upper zone, the duty cycle of the cooling system is decreased. Thus, the 2°C set-point increase on the main level is more effective than on the upper level as it allows the system to supply more cooling capacity where it is needed. This suggests that adjusting the supply fractions to correspond to cooling load fractions (if known) would be an improvement to the zoned system. The recovery period during the evening hours is also less pronounced as the heat build up on the main zone is not as extreme as on the upper zone observed in cases C1 and C2. Lastly, the upper level control period also extends later into the evening compared with C1 and C2, pushing the recovery period forward in time where cooling loads are no longer as significant.

Control strategies with the ‘zone cooling supply off’ condition (Figure 6.b) illustrate how the system responds when the thermostat set-point is incremented by a large margin, allowing the controlled zone temperature to free float during the control period.

The hourly averaged power profile for C1 (Figure 6.b) indicates that the system is off in the morning and early afternoon, corresponding to the upper and lower zone control periods. The system comes back on at 15:00 hrs as the control period for the main level ends. The system stays on for most of the afternoon and evening, recovering the heat accumulated in the two zones. The recovery time for the lower level is under an hour, since all of the capacity is sent to this level. The recovery time for the upper level (beginning at 19:00 hrs) is slower, although a comfortable temperature (~25°C) is reached after an hour. The slower response of the upper level is a consequence of the system capacity being split between the two levels in the evening hours when internal gains due to cooking on the lower level are high. Thus the upper level receives only half the system capacity, resulting in a slower recovery time. The results for C1 indicate that the on-off control action at 15:00 hrs on the lower level may not be desirable if peak electricity demand reduction is the goal. Alternatively, a gradual thermostat set-point decrease (e.g., 2°C /hr) may be more appropriate.

The hourly averaged power profile for C2 (Figure 6.b) shows a significant peak reduction throughout the afternoon, ending at 19:00 hrs at which point the upper level recovery period begins. Similar to C1, the upper level during the recovery period is only receiving half the system capacity as both upper and lower zones are calling for cooling in the early evening hours. Although the reduction in power consumption during the morning and early afternoon hours is not nearly as great as in C1 where both zones are free floating, avoiding any control actions in the afternoon hours results in a sustained reduction in power consumption throughout the day.

The hourly averaged power profile for C3 (Figure 6.b) shows a smaller reduction compared to C2. In fact, there is little difference between the 2°C incremental control and the cooling supply off control. This is largely due to higher cooling loads on the upper level. As a result, any control actions on the main level have a smaller effect on overall system response, which is governed by cooling loads on the upper level. It is interesting to note that the power profile for C3 does not exhibit a recovery period like C1 and C2. This is in part due to the lack of heat accumulation on the upper level, as well as the longer upper level control period (18:00 - 21:00 hrs). Extending the upper level control period to 21:00 hrs would have a similar effect in C1 and C2.

In general, there is a trade-off associated with the degree to which the set-point is increased during a control period. A higher set-point increase results in greater peak power reduction, but leads to greater heat accumulation and longer recovery time in the evening.

Addition of External Shading

As shown in Figure 7, solar loading accounts for the majority of the sensible cooling load on the upper and lower levels. To investigate the potential benefits of passive strategies as a complementary measure to the zoned cooling system, solar obstructions were added to the south facing windows of the model (Figure 8). The geometry of the obstructions is specific to sloped awnings.

Figure 9 shows the effect of the addition of awnings compared to the benchmark case B2, in which only internal venetian blinds are modeled. With the addition of external awnings, a significant reduction in hourly averaged power is clearly observed in the afternoon hours of the profile. The spike in power consumption in the early evening corresponds to internal gains associated with cooking and appliance use. The system is no longer running continuously and is now able to fully meet and exceed the cooling loads imposed on the space for peak summer day conditions. It is expected that with the addition of external shading, the zoned control strategies with 2°C set-point increase would have a more pronounced effect on reducing the peak power consumption.

It is worthwhile to illustrate the influence of other factors that account for the remainder of the cooling system power consumption, once the awnings have been included in the analysis. Figure 9 shows power consumption profiles for simulation runs in which cooling load factors are successively removed. First, make up air and envelope infiltration are removed (profile iii), followed by removing the influence of internal gains (profile iv). A significant portion of the cooling load is attributed to infiltration of hot and humid air (both make up air and envelope leakage). The internal gains due to cooking and appliance usage between 18:00 - 21:00 hrs also contribute considerably to the cooling load. Once infiltration and internal gains are removed, the remainder of the power consumption (profile iv) is due to envelope gains (a combination of solar heat gains and heat gains due to outdoor/indoor temperature differences).

CONCLUSIONS

The simulation results indicate that the effectiveness of zone control strategies during peak summer days relies to a large extent on the ability of the installed air conditioning capacity to meet the peak load. The

control scenarios with a 2°C set-point increase were largely ineffective in reducing electricity consumption during peak afternoon hours. Control scenarios with the 'zone cooling supply off' condition were more effective, but a greater heat build up and longer recovery time was observed. The results also suggest that ending a control period in the middle of peak hours should be avoided in order to prevent the cooling system from recovering any heat accumulation during peak hours. If necessary, a gradual set-point decrease if preferable to a sudden set-point drop. Control strategy C2 was shown to be the most effective, sustaining a significant reduction in power consumption throughout the afternoon hours. The addition of awnings to the south facing windows resulted in a considerable reduction in power consumption. Such a passive cooling measure is likely to increase the effectiveness of thermostat control strategies especially in homes with significant solar gains and air conditioners which tend to run continuously during peak summer days. The current study represents the first stage in the assessment of zoned systems on peak electricity demand. To provide more confidence in the model, the simulation results will be compared against measured data in the next stage of research.

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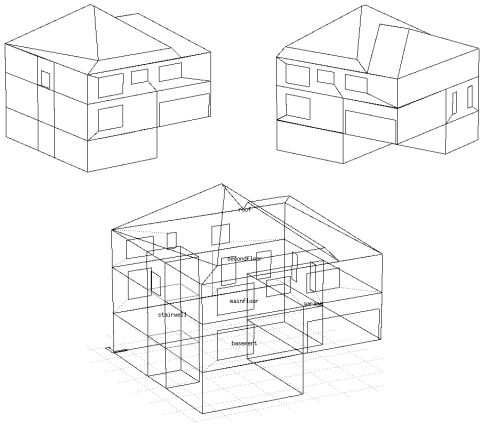


Figure 1: CCHT model geometry (front faces south).

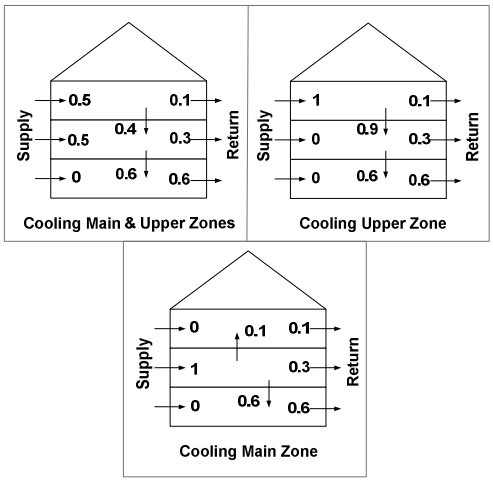


Figure 2: Mechanical ventilation balances.

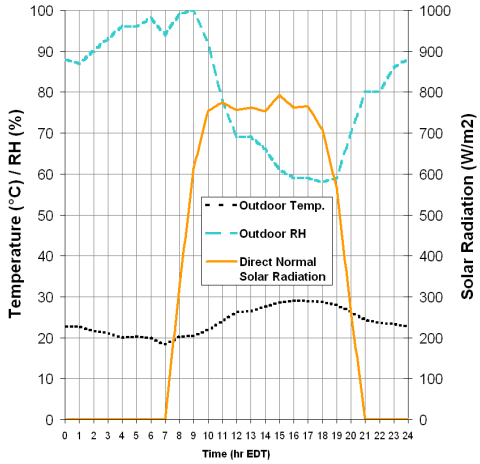


Figure 3: Weather data for Toronto on 08/31/2000.

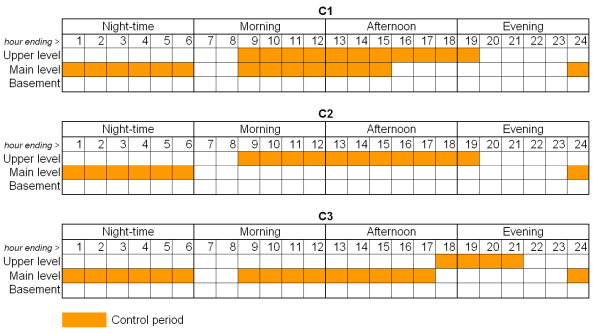


Figure 4: Zoned thermostat control scenarios.

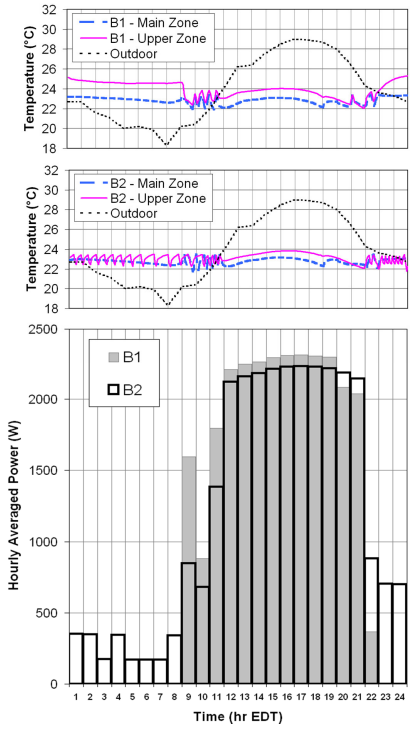


Figure 5: Hourly zone temperatures and averaged power profiles for cases B1 and B2.

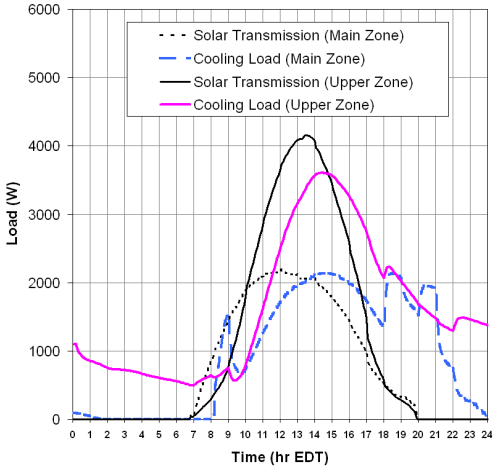


Figure 7: Ideal cooling loads and solar transmission.

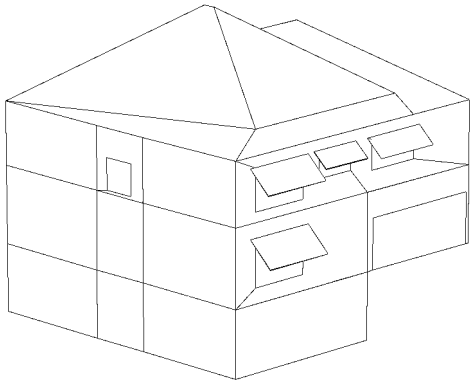


Figure 8: CCHT model with awnings on south side.

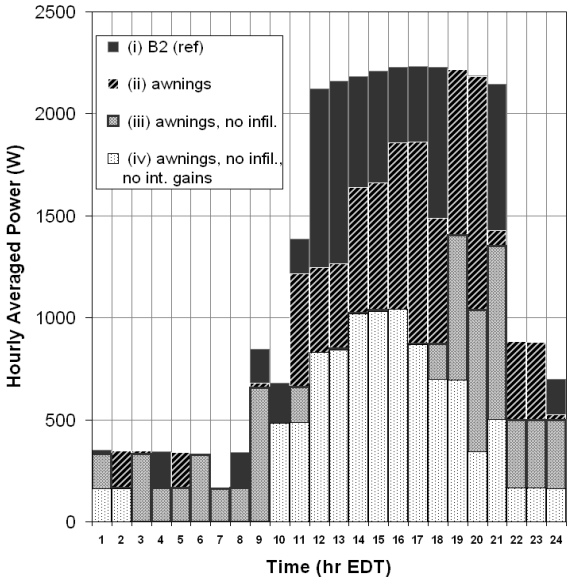
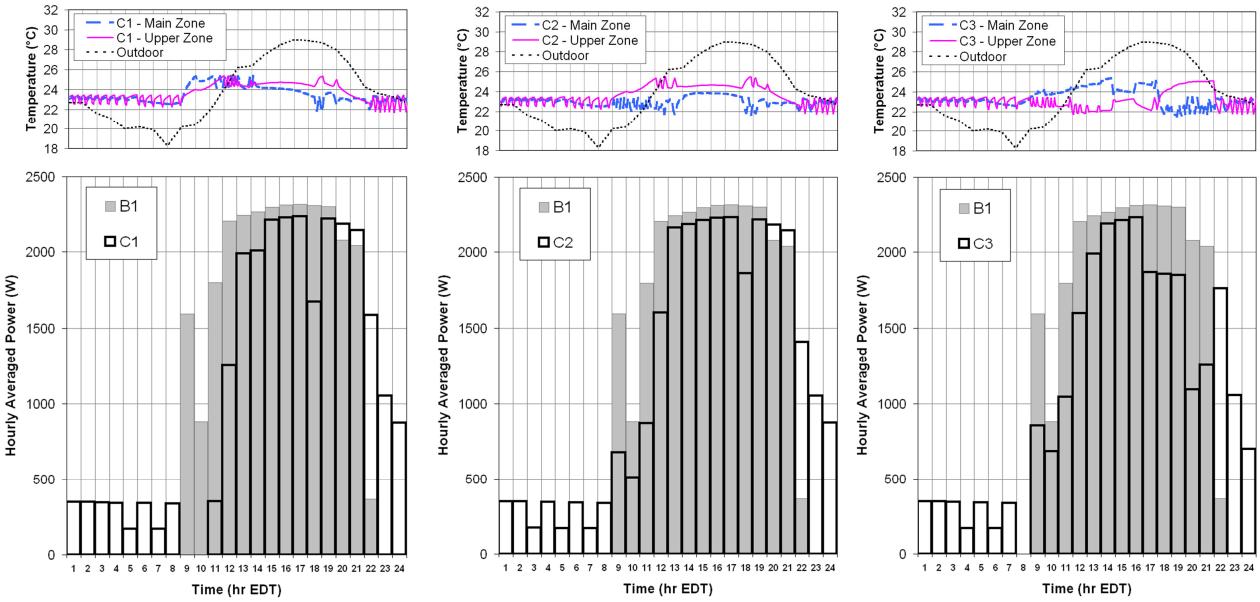
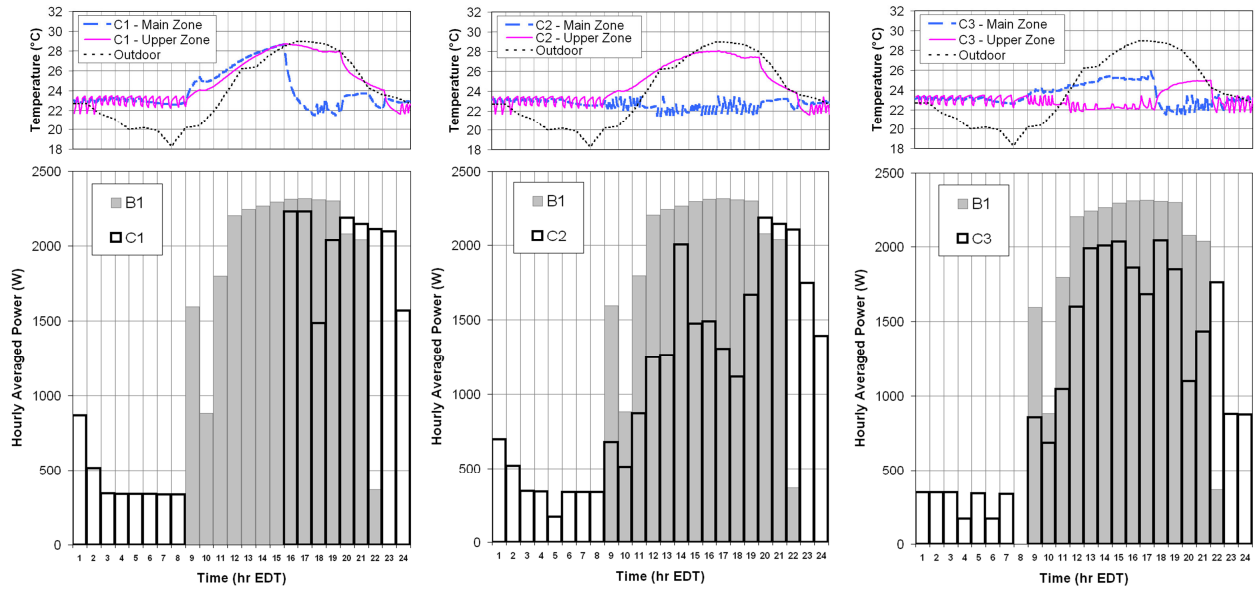


Figure 9: Effect of awnings and eliminated cooling load factors on the hourly averaged power profile.



a) 2°C thermostat set-point increase.



b) Zone cooling supply off.

Figure 6: Hourly zone temperatures and averaged power profiles for cases C1, C2 and C3.