Topic A7: Thermal comfort

THERMAL COMFORT DURING DIRECT LOAD CONTROL EVENTS IN UNIVERSITY LECTURE THEATRES

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SUMMARY

As a common approach to cope with air-conditioning peak demand, Direct Load Control (DLC) strategy has yielded positive results in Australian residential buildings. However, in university lecture theatres with high occupancy density and ventilation rate, thermal comfort impacts of DLC remain unclear. Designbuilder and Energyplus software were used to simulate thermal environments in a typical university lecture theatre during DLC events induced by different cycling schemes and building envelope thermal performance conditions. The analysis explores thermal comfort impacts by applying the PMV/PPD Index and the ASHRAE 55-2013 80% acceptability limit to simulated indoor climates. Results show that for the same DLC event, the ASHRAE adaptive 80% acceptability limit indicates less adverse thermal comfort impacts than the PMV/PPD index. For lecture theatres with poorer envelope thermal performance, DLC algorithms with high cycling levels (≥ 50%) should be avoided since they are very likely to induce unacceptable thermal environments.

INTRODUCTION

Universities in Australia and elsewhere are adversely impacted by peak electricity loads. To meet the peak demand, universities are required to pay substantial penalty rates. According to the network price list of a large utility company in Sydney, intuitional customers with a load of 750 MWh per annum or above will automatically be charged the KVA Demand Time-of-Use Tariff ($10.23/KVA in 2012). Universities typically consume more than 750 MWh of electricity annually. The peak demand used to apply the charge is the highest 30-min peak demand in the preceding 12 months. These events may only occur for a few hours in a year, but the universities end up paying the penalty, which takes up to 20% of the institution’s total electricity costs, for a whole year.

The Direct Load Control (DLC) strategy represents one of the most common approaches to managing demand. In DLC programs, an electricity utility or aggregator has the facility to remotely shut down or cycle high-demand electrical equipment (air-conditioners, water heaters, pool pumps, etc). This paper only discusses DLC of air-conditioners (AC). Typical DLC AC control approaches include duty cycle restriction and temperature setback (Weller, 2011). Duty cycle restriction involves cycling the AC compressor on and off at predetermined intervals. Under this program, the thermostat setting is maintained, but the AC compressor is only allowed to run for a predetermined time even if the set-point is not met, and then switched off (with the fan on) for a fixed period. By synchronizing and coordinating duty cycles across a large number of their customers, the aggregator can effect substantial load shedding during peak events.

Australian utilities like ETSA, Energex, Western Power, Ergon Energy have conducted trials on DLC AC duty cycle restriction in residential buildings in recent years. Generally speaking, these programs have reported positive results in reducing peak demands (peak load reduction per customer ranges from 13% ~ 35%) without causing excessive discomfort for customers (ETSA 2008, Energex 2010, Perth Solar City Annual Report 2012). However, to replicate the success of DLC in university classrooms, two factors must be taken into consideration before any realistic assessments can be made. First, the occupancy density in a classroom is much higher than in a residence, which means much higher internal loads in a classroom. Second, the high occupancy density in classrooms requires high ventilation rates. Commonly, classrooms have approximately 15 times greater ventilation density (outdoor airflow rate per floor area) than residences (Southern Energy Efficiency Center). The hot and humid outdoor air will be continually introduced into the building even when the AC compressor is cycled off, which may compromise occupants' thermal comfort during DLC events.

Predicting thermal environments during a DLC event is complicated because it depends on many factors, such as cycling schemes, cooling set-point temperatures, building thermal performance, ventilation rates, AC systems, control modes and so on. The aim of this paper is to present results of simulated thermal environments in a typical university lecture theatre during DLC events induced by various cycling schemes and different building thermal performance conditions, and to explore corresponding thermal comfort impacts on occupants by using PMV/PPD Index and ASHRAE 55-2013 80% acceptability limit.

METHODOLOGIES

Designbuilder Version 3.2, released in May 2013, and Energyplus 8.0.0.008, released in April 2013, are used in this simulation study. Designbuilder was used to set up the building geometry, building fabric and HVAC system configuration; Energyplus is then used to set up DLC control schemes as well as implement the thermal simulation.

Test Building and Systems

The Building under study is located in a university campus in Sydney, Australia. The two-level building, with a total floor area of 2, 230 m^2, has four lecture theatres, one tutorial room, one canteen, two offices and some other auxiliary spaces. Figure 1 illustrates the simplified Level 2 plan of the test building. The eastern and western entrances on Level 2 are the main entrances to the building. All four lecture theatres have identical dimensions: 18.8 m length × 15.7 m width × 8.4 m height. They can be accessed either from the back doors located on Level 2 or the front doors located on Level 1 foyer. There is no external window in this building except the glass gliding doors on both of the Level 2 Entrances and the pyramid roof skylight at the centre of Level 2 Foyer. The building is normally open from 7am to 6pm on weekdays during semester time, though it can be extended to 9pm or on Saturdays, depending on lecture theatre bookings. During non-semester time, lecture theatres are closed but the building common areas are open from 8am to 4pm.

The building was built in 1970 with a heating system serving four lecture rooms and the foyer areas consisting of a 200 KW natural gas boiler. The chilled-water system was installed around 1980. Chilled water is supplied at 6.1ºC by a packaged reciprocating chiller set and a chilled water pump, piped to four conditioners located in level 2 plant rooms. Each conditioner, comprising two cooling coils, has a cooling capacity of 123 KW and serves a large lecture theatre. Condenser water is supplied at 29.4 ºC to the chiller from a forced draught cooling tower via a condenser water pump. The chiller has a cooling capacity of 300.7 KW and COP of 3.89. Chilled water cooling coils operating between 6.1/12.8 ºC water temperatures provide the cooling throughout the building. The design air flow rate for each lecture theatre is 4.72 m^3/s and the cooling supply air temperature is 13.3 ºC. An automatic control system activates the chiller depending on a central time clock and a thermostat. The cooling set-point temperature is 22 ºC, which is the common practice in Australia. Capacity control is implemented by varying the chilled water flow rate using 3-way modulating control valves while the fan speed is constant. The tutorial room and the canteen each have their own Direct Expansion (DX) split system. Both Level 1 and Level 2 foyers are naturally ventilated.

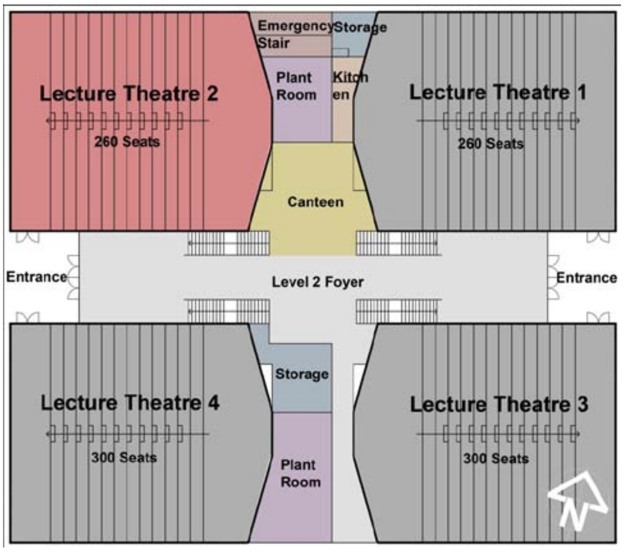

Figure 1. Simplified Level 2 Plan of the test building.

Simulation Models

Table 1. Internal loads for major spaces in the test building.

Spaces	Area (m^2)	Conditioned	Maximum Occupancy (people /m^2)	Maximum Lighting Density (W/m^2)	Equipment (W/m^2)
Lecture Theaters	288×4	Yes, Central AC	1.04 for Lecture 3 and 4; 0.9 for Lecture 1 and 2	6.9~13.4	2.1
tutorial room	56	Yes, Packaged DX	0.63	8.6	2
Foyers	396	No, naturally ventilated	0.05	10.2	8.5
Precinct offices	58	No	0.03	7.8	3
Canteen	55	Yes, Packaged DX	0.21	8.2	15
Kitchen	7	No	0.09	8	25
Toilets	99	No	0.11	5	5.6
Plant Rooms	62	No	0	5	50
Substation, Switch Room	97	No	0	5	30
Penthouses	40	No	0	2	40
Plinth Rooms	35	No	0	0	30

The model in Designbuilder has 65 zones and 65 component blocks. Investigations have been carried out in the test building to obtain actual internal load information, especially the occupancy schedule for model validation purposes. It is also found that although the lecture theatres can hold nearly 300 students, normal occupancy is only 60 ~ 140 students. Table 1 lists internal load inputs for main spaces in the test building.

The test building is in Climate Zone 5 in Australia, featuring warm and temperate climate (NCC, 2013). Hourly based TMY2 or WYEC2 weather files cannot be used for studying thermal impacts of sub-hour DLC schemes, so a decision was made to select a “real day” as the typical DLC event day and compile a user weather file from the real-time weather observations. All the weather data used in this study came from a nearby weather station (AWS). The selected DLC event day was 22nd March, 2013. For simulation of DLC events, a five-day 15-minute interval Energyplus Weather (EPW) file was compiled, containing the DLC event day and four previous days. Figure 2 demonstrates the dry bulb temperature, dew point temperature and relative humidity on the DLC event day.

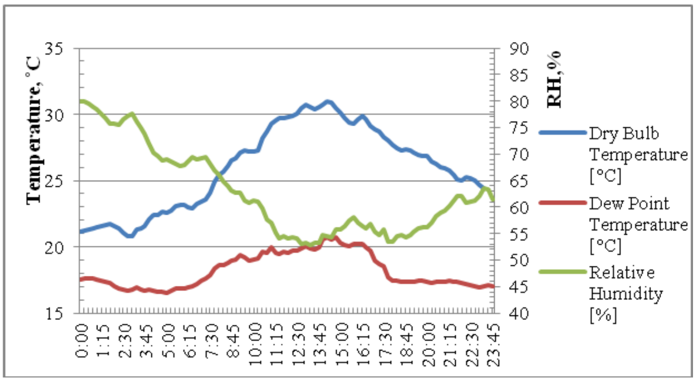

Figure 2. Outdoor weather on the selected DLC event day.

The “as built” simulation model was validated using available meter readings in two separate periods – July to October, 2012, and March to June, 2013. The occupancy schedules for the two validation periods have combined the booking information as well as the author’s actual observation. In July to October, 2012, the actual consumption was 128.8 MWh while 137.3 MWh for simulation, with an acceptable error of 6.6%; in the period 08/03 ~21/06 in 2013, the actual consumption was 119.8 MWh and 110.5 MWh for simulation (error 7.7%).

Parameters for Simulation

Cycling levels refer to the amount of time the AC compressor will be off during an activation period (Newsham et. al., 2010). According to previous DLC studies, 50% cycling level and 0.5 hour cycling period are the most commonly used cycling schemes. Other cycling levels, such as 30%, 33%, 65%, 75%, 100% and different cycling periods, such as 1 hour, have also been used. In this study, three cycling levels - 33%, 50% and 67%, and two cycling periods - 0.5 hour and 1 hour are tested in simulation.

Two levels of building envelope thermal performance conditions typical for Australia’s university building stock were selected for this study. One is the original test building fabric for external walls and roofs, representing the uninsulated 1970’s building stock; the other one is selected from the “Best Practice Wall, heavyweight” and “Best practice Flat roof (no ceiling), Heavyweight” in Designbuilder building construction database, representing the insulated new building. Detailed building fabric layers and corresponding U-Values are listed in Table 2. Internal building specifications remain in the “as built” condition across all of the project’s simulation scenarios. Through all simulations, the cooling set-point temperature was fixed at 22 ºC, and the building ventilation rate set to 10 L/s/person, which complies with the minimum requirements in Australian Standard 1668.2 (1991). The infiltration rate for the whole building was set to 1 ac/h.

Table 2. Two levels of building envelope fabric and U-Value for the test building.

Two Levels of Building Thermal Performance	Building Envelope			
	External Walls		Roofs	
	Layers	U-Value	Layers	U-Value
Old Building without insulation	110mm brick, 100mm timber stud+ 260mm air space non reflective and unventilated, 10mm gypsum plasterboard	1.914	10mm PVC, 40mm Floor/Roof Screed, 130mm Concrete Reinforced	2.520
New Building with insulation	105mm brick, 118.2mm XPS extruded polystyrene, 100mm concrete block, 13mm gypsum plastering	0.251	19mm asphalt, 13mm fibreboard, 205mm XPS extruded polystyrene, 100mm cast concrete	0.149

For parametric studies, Lecture Theatre 2 (in Red in Figure 1) was selected as the test bed of the DLC event simulation since it is located in the north-west of the building and can serve as a “worst case” scenario in the hot afternoon. The event lasts for 3 hours from 2 pm to 5 pm. During the event, it was assumed that Lecture 2 held 130 students; the lighting load was 3 KW and equipment load 0.6 KW. Internal loads and schedules for other lecture theatres or spaces in the building remain the same as in the validation model. Direct load control was imposed on the original HVAC systems by setting up a cycling schedule to the chilled water loop. Assumptions for thermal comfort simulation are: the clo value for all occupants is 0.5 (0.4 for clothing and 0.1 for chairs). The Metabolic Rate is 1.2 Met for sedentary occupants reading and learning. The indoor air speed is the default value in Designbuilder - 0.137 m/s.

RESULTS AND DISCUSSION

This study combines simulation scenarios for 3 cycling levels, 2 cycling periods and 2 building thermal performance conditions, yielding 12 simulation cases. For each case, the operative temperatures, PMV and PPD during the DLC events are plotted from Energyplus.

Most present thermal comfort standards require that thermal environment should be within a certain range to guarantee comfort for occupants. They also prohibit large temperature fluctuations which are not under the direct control of individual occupants to keep thermal environment in a relatively static condition. However, duty cycle restriction in a DLC event will cause rises and falls in operative temperature. Since the cycling periods for all DLC events under study are longer than 15 minutes, they should be treated as temperature drifts according to ASHRAE 55 (2013) and should comply with the temperature limit specified in Table 3. However, examination of simulation results show that actual operative temperature changes in specific time periods during DLC events are all higher than permitted by ASHRAE 55 (2013), as can be seen in Table 3. It reveals that duty cycle restriction in a DLC event will cause larger temperature fluctuations than what is allowed in ASHRAE standard.

Since the PMV/PPD model was derived in a controlled climate chamber under steady conditions, and the ASHRAE 55-2013 adaptive model is designed for occupant-controlled naturally conditioned spaces, neither model may be fully appropriate to predict thermal comfort impacts during DLC events, so in this study they serve merely as indicative thermal comfort indexes. The actual thermal comfort impacts of DLC events can only be obtained from replicating simulated DLC events in laboratory experiments, or in actual field studies.

Table 3 ASHRAE 55 permissible and simulated temperature changes for temperature drifts

Time Period, h	0.25	0.5	1	2	4
Maximum Operative Temperature Change Allowed in ASHRAE 55-2013, °C	1.1	1.7	2.2	2.8	3.3
Time Period, h	0.2	0.25	0.5	1	
Maximum Operative Temperature Change Achieved for good insulation scenarios, °C	1.8	2.2	3.3	4.3	
Maximum Operative Temperature Change Achieved for poor insulation scenarios, °C	1.9	2.3	4.2	5	

PMV/PPD Model as a Thermal Comfort Index

As is stated in ASHRAE 55 (2013), PMV/PPD is widely used to determine the requirements for thermal comfort in occupied spaces. It recommends that PMV should be in the range of -0.5 to 0.5 and PPD within 10%. Figure 3 illustrates the maximum PMV and PPD values in 12 simulation scenarios. The mean of maximum PMV is 0.7 ± 0.3 (standard deviation). Only 3 scenarios restrained the max PMV below 0.5. There are 3 scenarios in which max PMV is over 1. In these scenarios, cycling levels are no less than 50% and the thermal performance condition is poor. The mean of maximum PPD is 19.2% ± 8.6% (SD) and max PPD value in only one scenario is within 10%. The 3 scenarios with max PMV value greater than 1 have the max PPD value higher than 25%.

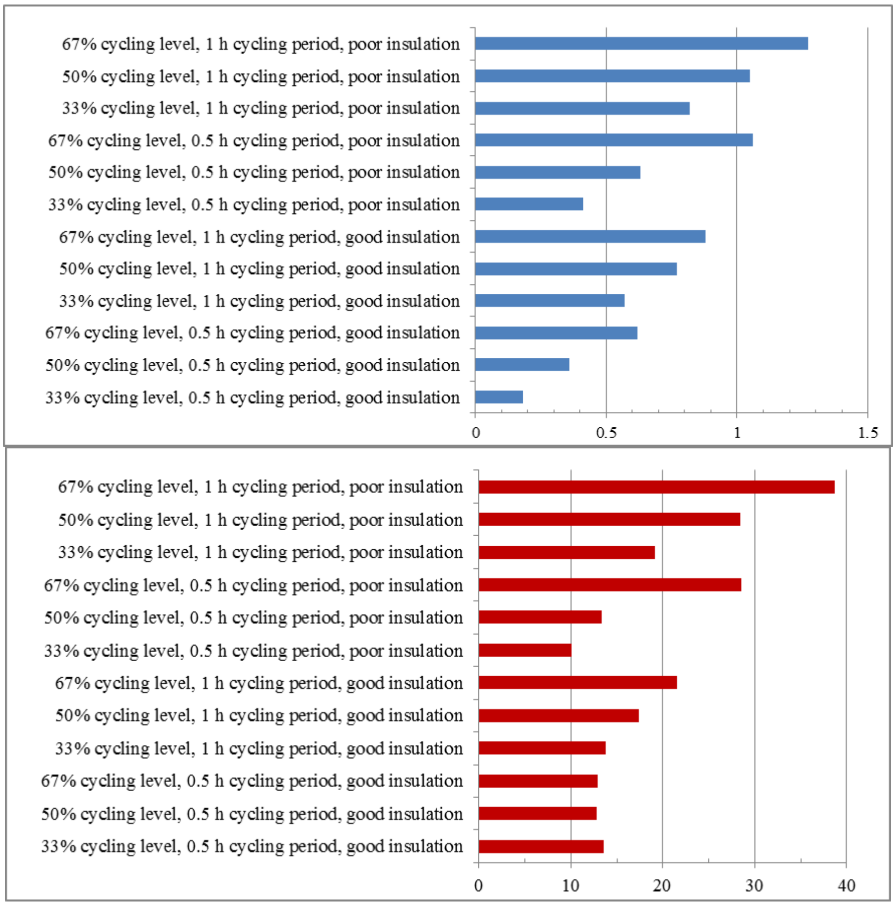

Figure 3. Maximum PMV and PPD value in 12 DLC scenarios.

Figure 3 reveals that most DLC scenarios have exceeded the permissible thermal comfort range by PMV/PPD methods specified in ASHRAE 55-2013. Though PMV/PPD may not be strictly appropriate for DLC events, previous laboratory studies on temperature transients (Griffith and McIntyre 1974, Knudsen et al 1989, and Kolarik et al 2009) have reported that for temperature ramps with moderate temperate changing rate, subjects' thermal sensation and thermal acceptability generally agree with predicted by PMV/PPD Model. However, there is no consistent conclusion on the limit of the temperature changing rate within which PMV/PPD will be valid. Still, the suitability of PMV/PPD model for application to DLC events needs to be tested in laboratory experiments and field studies.

ASHRAE 55-2013 Adaptive 80% Acceptability Limit as a Thermal Comfort Index

The ASHRAE adaptive thermal comfort model relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters (the prevailing mean outdoor temperature). The prevailing mean outdoor temperature for the DLC event day is an exponentially weighted (α =0.8 for this case) running mean of 7 days of mean daily outdoor temperatures prior to the DLC event day (ASHRAE 55, 2013). The permissible indoor operative temperature was determined using the 80% acceptability limit, which is 27.7 °C based on calculation. The operative temperatures in all DLC simulation scenarios will be compared to this limit to indicate the possibility of a thermal environment being accepted. Across 12 scenarios, the average maximum operative temperature is 26.8 °C with a standard deviation of 1.1 °C.

Table 3 lists DLC scenarios in which operative temperatures fell above the ASHRAE 55-2013 adaptive 80% acceptability limit and the percentage of time beyond it. Out of 12 scenarios, three have exceeded the limit, two of which for less than 10% of the event duration. Most simulated DLC scenarios fell within the limit, and for those exceeding it, only one scenario with 35% of time beyond the limit is likely to cause substantial occupant thermal discomfort. It can also be found that these 3 scenarios are the same 3 scenarios which have max PMV greater than 1 and max PPD higher than 25%. This strongly suggests that high cycling level DLC algorithms in lecture theatres with poor insulation are very likely to generate unacceptable thermal environments.

Table 3. DLC scenarios exceeding the ASHRAE 55-2013 adaptive 80% acceptability limit.

Cycling Levels (%)	Cycling Periods (h)	Building Thermal Performance Condition	Maximum Operative Temperature	Proportion of time operative temperature is above ASHRAE 55-2013 Adaptive 80% Acceptability Limit
67	0.5	Poor	27.8	1.1%
50	1	Poor	28.0	6.7%
67	1	Poor	28.7	35%

CONCLUSIONS

By simulating a typical university lecture theatre in Designbuilder and Energyplus, this study has explored thermal comfort impacts of DLC events induced by various cycling levels, cycling periods and building thermal performance by using PMV/PPD and ASHRAE 55-2013 adaptive 80% acceptability limit. Results show that duty cycle restriction in a DLC event will cause larger PMV/PPD fluctuations than permitted by ASHRAE 55-2013. For the same DLC event, the ASHRAE adaptive 80% acceptability limit indicates less adverse thermal comfort impacts than the PMV/PPD index. However, actual thermal comfort impacts of DLC events can only be obtained from laboratory experiments or field studies. For lecture theatres with poorer envelope thermal performance, DLC algorithms with high cycling levels ($\geq$ 50%) should be avoided since they are very likely to induce unacceptable thermal environments.

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