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Thermal environments and thermal comfort impacts of Direct Load Control air-conditioning strategies in university lecture theatres

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ABSTRACT

As a common approach to manage peak electricity demands associated with air-conditioning (AC), the Direct Load Control (DLC) strategy has yielded positive results in residential and small commercial buildings in countries that include USA, Australia and Canada. However, in educational settings with high occupant density and ventilation requirements, thermal comfort impacts of DLC remain unclear. EnergyPlus was used to simulate thermal environments inside a typical Australian university lecture theatre during DLC events under various cycling schemes, cooling set-point temperatures, building envelope thermal performance specifications and ventilation rates. The analysis explores thermal comfort impacts by applying the PMV/PPD index to simulated indoor climates. Results indicate that off cycle fraction (duration of AC compressor being off during an activation period), cycling period (time for a complete cycle) and cooling set-point temperature have relatively large influences on occupant comfort compared to the building envelope's thermal performance and ventilation rate. In order to maintain acceptable thermal comfort for occupants, DLC algorithms must be applied judiciously and customized to the specific building. All else being equal, DLC algorithms with shorter cycling periods have less adverse thermal comfort impacts than the longer ones.

1. Introduction

As large institutional consumers universities are adversely impacted by peak electricity loads. To meet the peak demand, universities in Australia are levied substantial penalty rates. According to the network price list of a large utility company in Sydney Australia, institutional customers with a load no less than 750 MW h per annum will automatically be charged the kVA Demand[1] Time-of-Use Tariff (US $9.44/kVA in 2012). Many Australian universities have exceeded the 750 MW h annual consumption thresholds and in Sydney the kVA Demand Time-of-Use Tariff is applied to the highest 30-min peak demand in the preceding 12 months. Peak demand events may only occur for a few hours in a year, but this kVA Demand Time-of-Use can represent 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 peak electricity 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 [2]. 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. Off cycle fraction refers to the amount of time the AC compressor will be off during an activation period. Cycling period is the time for one complete cycle of AC compressor on and off. By synchronizing and coordinating duty cycles across a large number of their customers, the utility company or the aggregator can effect substantial load shedding during peak events.

Many utility companies in USA, Australia, and Canada have conducted trials on DLC AC duty cycle restriction in residential and small business buildings in recent years (shown in Table 1).

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[1] Demand is a measure of the maximum amount of electricity being drawn from the grid over a half-hour interval. It may be measured in units of kVA or kW. Demand charges from the utility are typically levied on the customers' maximum demand for a particular time period. Depending on the network tariff, demand charges may be split into time of use periods. Furthermore, demand may be measured in rolling periods, e.g. highest demand for the last 12 months [1].

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Table 1
Representative DLC programs or trials in recent years.

DLC programmes or trials	Country	Year	Customer segment addressed	Off cycle fractions	Cycling periods	DLC event duration	Customer feedback on comfort	References
ETSA Utilities Residential Direct Load Control Trial	Australia	2005–2008	Residential	25%, 50%	0.5 h, 1 h	1 – 3 h	No customer complaints	[3]
PG & E's SmartAC Program	USA	2007	Residential and small business	50%	0.5 h	Up to 6 h	9% discomfort	[4]
BGE Demand-Response Infrastructure Pilot	USA	2007	Residential	30%, 50%, 75%	0.5 h	4 – 5 h	"Comfort issues due to cycling were not a major concern"	[5]
2010 Hydro Ottawa Peaksaver® Program	Canada	2010	Residential and small business	30%, 50%	Not stated	Up to 4 h	12% – 17% discomfort	[6]
Perth Solar City Air-conditioning Trial	Australia	2010–2012	Residential	33%, 50%	0.5 h	Up to 4 h	76% of participants felt "no change" in comfort levels	[7]

Generally speaking, these programs have reported positive results in reducing peak demands without prompting excessive complaints from customers. However to replicate the success of DLC in university lecture theatres two factors must be taken into consideration before any realistic assessments can be made. First, the occupant densities (internal loads) in a lecture theatre are much higher than in a residence. Second, the high occupant density in lecture theatres requires much higher ventilation rates. Classrooms commonly have approximately 15 times greater ventilation volumes (outdoor airflow rate per floor area) than residences [8]. The hot and frequently humid outdoor air that triggered the peak demand event in the first place will be continually introduced into the lecture theatre even when the AC compressor is cycled off, which may compromise occupants' thermal comfort during DLC events.

Indoor thermal environmental conditions during a DLC event depend on many factors including off cycle fraction (the amount of time the AC compressor is off during an activation period), cycling period (time for a complete cycle), cooling set-point temperature, building envelope thermal performance, ventilation rate and so on. By setting up a building and system model in building thermal simulation software, thermal environments during a DLC event can be predicted. In the literature, many building simulation studies address building energy consumption, energy conservation measures and occupant comforts in various built environments [9–13]. In relation to DLC, the extensive recent studies have mainly focused on aggregated load modelling, control strategies and prediction of demand savings [14–18]; no studies concentrating on the thermal environments and thermal comfort during DLC events have been published to date.

Peak load reduction and maintenance of comfort are two important goals for DLC programs, and DLC scenarios should be evaluated from both perspectives. However, at a micro level (single building or customer), the peak load reduction is not readily discernible due to the "rebound effect" [14,19] which refers to the even higher peak load often occurring immediately after the load shedding period. But at a macro level (utility companies or the aggregators), a large number of participating customers with staggered DLC events for sub-groups of customers can still achieve substantial peak load reduction over and above the rebound of sub-groups. This paper does not address demand saving aspects of DLC scenarios, but rather focuses on the thermal comfort impacts on occupants at the single-building scale. It aims to present results of simulated thermal environments within a typical university lecture theatre during DLC events, as induced by various off cycle fractions, cycling periods, cooling set-point temperatures, building envelope thermal performance and ventilation rates.

2. Methodology

DesignBuilder (Version 3.2, released in May 2013), and EnergyPlus (Version 8.0.0.008, released in April 2013), were used in this simulation study. DesignBuilder was used to set up the building geometry and HVAC system configuration; EnergyPlus was then used to set up DLC control schemes and implement the simulation.

2.1. Test Building and System description

2.1.1. Building

The building under study is located in a university campus in Sydney, Australia. This two-level building has a total floor area of 2230 m^2, comprising four lecture theatres, one tutorial room, one canteen, two offices and some other auxiliary spaces. Fig. 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 are no external windows in this building except glass gliding doors on both Level 2 entrances and the pyramid roof skylight at the centre of Level 2 foyer. The building is normally open from 7 am to 6 pm on weekdays during semester time, though it can be extended to 9 pm or on Saturdays, depending on lecture theatre bookings. During non-semester time, lecture theatres are closed but the building common areas are open from 8 am to 4 pm.

2.1.2. HVAC systems

The building was built in 1970 with a 200 kW natural gas boiler heating system serving four lecture theatres and the foyer areas.

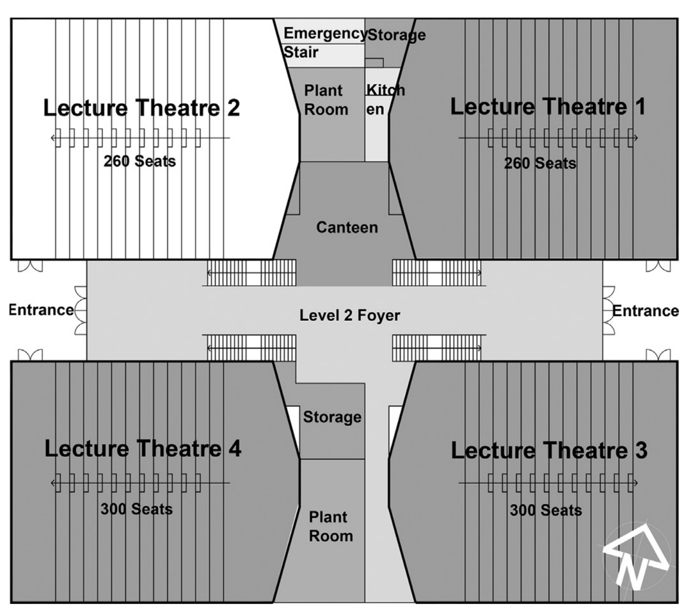

Fig. 1. Simplified Level 2 plan of the test building.