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Thermal performance of 6 star rated houses in the hot and humid tropical climate of Darwin

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Abstract

This paper evaluates the post-occupancy performance of 6 star houses in the hot and humid tropics of Darwin compared to unrated/lower rated control houses during the inactive/active phases (build-up/wet) of monsoon trough. Study is based on surveys of 61 respondents in the build-up and 44 respondents in the wet, indoor climatic measurements in 10 houses, and electricity consumption data. Actual mean vote ranged between -0.5 to 0.5 at a range of mean indoor conditions: air temperature 29.9-30.72°C, relative humidity 50.42-72.96%, and air velocity 0.23-0.35m/s. Behavioural adjustment surveys showed that the percentage of occupants in 6 star rated houses who always utilise air conditioner increased from 36% in the build-up to 50% in the wet. While percentage of fan users remained around 90% during both periods. An impact of occupants' behavioural adjustment, house star rating, and built environment on indoor climatic conditions is discussed through analysis of monthly mean temperature and relative humidity values. Mean monthly air temperature in living rooms of 6 star houses reached highest point of 30.8°C in February 2016; while in control houses it reached 31.59°C in January 2016. Highest mean relative humidity in 6 star rated houses was 74% compared to 81% in control houses. Analysis of electricity consumption of 36 households showed that the average half-hourly consumption of households in 6 star rated houses increased from 0.58 kWh in December 2015 to 0.72 kWh in February 2016, while consumption in control houses increased from 0.72kWh in December 2015 to 0.76kWh in January 2016, and reduced to 0.75kWh in February 2016. This paper presents findings for the build-up and wet seasons only. The results of this study provide insight into the impacts of the built environment, thermal preferences, and occupant behavioural adjustment on the thermal performance and electricity consumption of households in hot and humid tropical conditions.

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Keywords: Thermal sensation; building energy efficiency; behavioural adjustment

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1. Introduction

The small margin between the upper limit of thermal comfort and the “onset of …serious heat stress” [1, p 168] indicates the importance of accurate thermal comfort assessment and prediction for human wellbeing in tropical regions. There have been a number of studies conducted on the impact of hot and humid tropical conditions on human comfort, health and working activity. Early qualitative research showed that conditions at effective temperature (ET) above 27°C and relative humidity above 72% were uncomfortable for more than 80% of respondents and similar results were found in Weipa study [2, 3]. Thermal comfort study in Darwin, consisting of 31 household during six weeks of the build-up and wet seasons, showed that the Actual Mean Vote, based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) scale [4], ranged from 0.45-0.65 for siting and active subjects (clo level of 0.35) at mean air temperature range 29.4-30.6°C, mean relative humidity 60-72%, and mean air speed 0.01-0.3m/s [5]. Chamber studies also identified that humans feel fatigued working for 180 minutes in the room with air temperature at 30°C and relative humidity at 70% [6]. Temperatures above 29.4°C with relative humidity above 70% were found to increase the number of cardiovascular and respiratory patients in hospital [7, 8]. Other studies show that people living in hot and humid tropical climates can adapt to the thermal conditions in naturally and mechanically (fan) ventilated buildings, by drinking water, taking showers, changing clothes and using fans [9-11]. These qualitative studies also supported by a chamber experiment on 19-25 year old female subjects [12]. Study participants, wearing clothing with an insulation value of 0.3 clo and situated in front of the fan, felt thermally comfortable at 30°C air temperature and 80% relative humidity only if the air movement was 1.27 m/s [12].

There are ongoing debates among scholars regarding factors that have the most impact on human thermal comfort, and which indices are most suitable for measuring thermal comfort, modelling urban spaces and predicting the energy efficiency of buildings [13]. The requirements of International Standard ISO 7730 for thermal conditions are based on Fanger’s heat balance approach using the Predicted Mean Vote (PMV) method that predicts thermal comfort in air-conditioned buildings [14]. Another index used to predict thermal comfort is standard effective temperature (SET), the equivalent temperature of an environment at sea level at 50% relative humidity in which a subject wearing standardised for activity clothes would have the same skin temperature and skin wittedness as in the actual environment [15]. The SET values of 22-25.6°C is equivalent to neutral sensation on PMV scale [16]. In Australia, the National House Energy Rating Scheme (NatHERS), the main tool used to simulate thermal performance of detached houses, requires the consideration of natural ventilation, mechanical cooling (fans) and air-conditioning as the main means applied to achieve thermal comfort of occupants. NatHERS adopted the new Effective Temperature (ET*) index for assessment of indoor thermal comfort and uses the approximation of ET* and neutral temperature based on mean monthly outdoor temperature [16-18].

This study aims to investigate thermal performance of 6-7 star rated houses, built in subdivision, designed to provide local breezes and natural ventilation for houses in the hot and humid tropical climate. The main research objectives of this study is to determine indoor climatic condition in 6 star rated houses, investigate occupants’ thermal sensations, preferences and behavioural adjustment, and compare energy consumption of households of 6-7 star rated houses to households living in control houses.

2. Methodology

2.1. Study area

Darwin is situated within Australia’s wet and dry tropical climate zone, characterised by a hot and humid ‘wet season’, that starts with build-up in November and a ‘dry season’ from May to September, with transitional months generally occurring in April and October. However, seasonal and daily temperature changes are marginal; the daily mean maximum temperature is 33.3°C in November and 30.6°C in June and July [19]. Mean humidity levels in Darwin range from 58% to 83%. South-easterly and easterly winds occur for most of the year. Darwin’s transitional and wet seasons are characterised by low percentage of wind occurrence, low wind speed and high relative humidity in the mornings, while afternoon observations show stronger winds and 10-15% lower relative humidity.

2.2. Thermal performance

This study was carried out in two suburbs of northern Darwin built between 2009 and 2016 (Lyons and Muirhead). All houses in Muirhead have been designed to meet the NatHERS 6 star or higher rating and aim to utilise mixed-mode cooling of indoor climate throughout the year: air-conditioning, mechanical ventilation and natural ventilation. The design of the Muirhead subdivision is intended to promote natural house ventilation through parallel roads, orientation of lots (30 degrees north) to capture prevailing breezes, and provision of wide setbacks. Most houses in Lyons were designed and built before the Building Code of Australia (BCA) 2009 energy efficiency requirements were implemented in the Northern Territory, and have been used in this study as controls.

Thermal sensation surveys of participants in build-up and wet season, conducted along spot measurements of internal thermal conditions in 6-7.5 star rated houses (further referred as SR houses) and in control houses (further referred as C houses). Surveys were designed as once-off sampling taking into account the very marginal change in temperature. Half-hourly longitudinal measurements of indoor climatic conditions (air temperature, humidity, and air velocity) in the living rooms of 10 participating houses (5 SR and 5 C houses) were recorded and analysed. HOBO UX100 data loggers were used for air temperature and relative humidity monitoring. Hot wire anemometers were used for air velocity monitoring. Half-hourly energy consumption of 18 SR houses and 18 C houses of comparable construction type (Table 1) was assessed based on data provided by Power and Water Corporation.

Table 1. Construction types of study houses

Construction type	Conditioned floor area (m^2)	SR houses	C houses	Total
Single storey, concrete slab on ground, blockwork wall, insulated colorbond roof, insulated ceiling (SSCSBW)	95-180	16 (6-6.5 star)	16 (1 house 5.5 star)	32
Two storey, concrete slab on-ground, blockwork ground floor, lightweight first floor	180	0	1	1
Lightweight elevated house, insulated custom orb metal roof and walls, high ceiling (LWEL)	154	0	1	1
Lightweight, single storey, concrete slab on-ground, structural insulated panels, insulated colorbond roof, insulated ceiling (LWSSCS) and fibro clad framed insulated walls and roof/ceiling attic continuous insulated.	61-129	2(6-7.5 star)	0	2

2.3. Thermal sensation survey

Thermal sensation and behavioural adjustment of house occupants was investigated through two surveys undertaken alongside spot measurements of indoor climatic conditions (air temperature, relative humidity, and air speed). Surveys were conducted any time between 9am and 5pm, as convenient for participants. Participants were asked to fill out questionnaires that have two parts. The first part of the questionnaire collected information on demographic and personal data, thermal sensation based on ASHRAE scale, air humidity, and air movement sensations. The ASHRAE scale is a seven-point scale of thermal sensation: -3 cold, -2 cool, -1 slightly cool, 0 neither cool nor warm, 1 slightly warm, 2 warm, 3 hot. Air movement sensation is represented on seven point scale: -3 too still, -2 still, -1 slightly still, 0 neither still nor breezy, 1 slightly breezy, 2 breezy, 3 too breezy. Air humidity sensation is also represented on seven point scale: 3 very dry, 2 dry, 1 slightly dry, 0 neither dry nor humid, -1 slightly humid, -2 humid, -3 very humid [20, 21]. Surveys were carried out in the build-up between 11 November and 7 December 2015, and in the wet season 10-29 February 2016.

Three thermal comfort indices were calculated and compared: Actual Mean Vote (AMV), Predicted Mean Vote (PMV), and Standard Effective Temperature (SET). PMV and SET were calculated using the thermal comfort tool developed by Centre for the Built Environment at the University of California Berkeley [22]. All required data for PMV calculation was collected during surveys except mean radiant temperature, accepted as being equal to dry bulb temperature based on results of previous thermal comfort studies [10, 23].

The second part of the questionnaire collected information on the behavioural adjustment of house occupants, such as usage frequency of air conditioner, fan/fans, windows and doors. The majority of participants filled out questionnaires sitting at the table in the living room, so spot measurements were conducted one meter above the floor. Thermal comfort surveys of occupants of SR and C houses are aimed to investigate the thermal preferences and behavioural adjustment of occupants, and identify the thermal comfort indicator that correlates closely with actual mean vote.

3. Results and discussion

3.1 Thermal comfort

The majority of participants were young adults, equally distributed between the ages of 25-34 and 35-44 (Table 2). In terms of gender distribution, males and females were almost equally represented in both surveys. Tenure type was taken into account because households renting houses mainly represent interstate migrants who have spent a shorter period in hot and humid climatic conditions. Owners presented 68% of participants during the first survey and 72% during the second survey.

Table 2. Demographic distribution of study participants

		Build-up	Wet
Number of respondents		61	44
	SR	31	24
	C	30	20
Age group		30% (25-34), 34% (35-44), 12% (45-54), 16% (55-64), 8%(65+)	36% (25-34), 36% (35-44), 14% (45-54), 5% (55-64), 9% (65+)
	SR	42% (25-34), 39% (35-44), 3% (45-54),13%(55-64), 3% (65+)	50% (25-34), 42% (35-44), 4% (45-54), 4%(65+)
	C	17% (25-34), 30% (35-44), 20%), 20% (45-54), 13% (55-64)	(20%(25-34), 30%(35-44), 25%(45-54), 10%(55-64), 15 % (65+)
Gender		F (56%), M (44%)	F (57%), M (43%)
	SR	F (52%), M (48%)	F (54%), M (46%)
	C	F (60%), M (40%)	F (60%), M(40%)
Number of households		38 (SR -18, C -20)	32 (SR-16, C-16)
Tenure		Own (25) Rent (13)	Own (23) Rent (9)
	SR	Own (14) Rent (4)	Own (14) Rent (2)
	C	Own (11) Rent (9)	Own (9) Rent (7)
Household type	SR	2-3memb (8), 4-5memb (9), 6-8memb (1)	
	C	2-3memb (11), 4-5 memb (7), 6-8 memb(2)	

During surveys, some participants filled in questionnaires in air-conditioned living rooms (windows and doors closed), and others had open windows/doors and fans switched on (Table 3). Indoor mean air temperature in air-conditioned rooms of SR houses increased from 28.4°C in the build-up to 29.9°C in the wet, while mean values of relative humidity stayed the same. Mean air temperature in naturally and fan ventilated rooms of SR houses was slightly higher than in air-conditioned rooms; however mean relative humidity was higher by 13-23%. Mean air velocity in naturally and fan ventilated rooms was 0.35m/s compared to 0.23m/s in air-conditioned rooms in the wet season. Mean clo value ranged from 0.22clo to 0.27clo for participants in naturally and fan ventilated rooms in SR houses, and 0.26clo to 0.3clo in air-conditioned. Mean clo value ranged from 0.22clo to 0.29clo for participants in air-conditioned rooms of C houses and from 0.27clo to 0.29clo in naturally and fan ventilated rooms.

Results of the thermal comfort surveys show that mean thermal sensation of participants in air-conditioned rooms of SR houses was between ‘slightly cool’ and ‘neither cool nor warm’ points during the build-up (survey I) and the wet (survey II) with AMV range -0.5–-0.57. While participants in naturally and fan ventilated rooms of SR houses felt between ‘neither cool nor warm’ and ‘slightly warm’ sensations, with AMV reduced from 0.59 in the build-up to 0.5 in the wet.

The mean vote of participants in air-conditioned rooms of C houses was close to ‘neither cool nor warm’ sensation. AMV in naturally and fan ventilated rooms of SR houses was 0.23 points lower than in C houses in the build-up and 0.64 points lower in the wet. AMV of 0.59 for naturally and fan ventilated rooms in SR houses during the build-up is close to AMV of 0.6 (4.6) received in 1988 survey[5], while AMV of respondents for air-conditioned rooms of SR houses is 1.22 points lower than in 1988 survey [5]. AMV of respondents in naturally and fan ventilated rooms in C houses during the wet season was 0.55 points higher than AMV received in the same period in 1989 [5]. This can be explained by higher mean dry bulb temperature of 29.45°C in February 2016 compared to 28.4°C in February 1989 [5] and smaller sample.

Table 3. Thermal sensation vote and indoor climatic conditions

Houses	Survey	No of respondents		Ta, °C	RH, %	Va, m/s	SET, °C	AMV	PMV
SR (A/C, A/C and Fans)	I	14	Mean	28.4	50.93	0.38	24.74	-0.57	-0.06
	II	16		29.65	50.42	0.23	27.21	-0.5	0.93
	I		Min	27.02	37.56	0.06	21.97		-1.15
	II			27.55	39.39	0.04	22.90		-0.76
	I		Max	32.07	60	0.7	29.04		1.52
	II			32.42	57	0.72	32.82		3
SR (Fans, windows and/or doors opened)	I	17	Mean	31.73	63.85	0.36	28.47	0.59	1.42
	II	8		30.72	72.96	0.35	28.06	0.5	1.11
	I		Min	29.77	51.61	0.13	25.08		0.53
	II			30.17	58.79	0.04	25.50		0.3
	I		Max	33.99	79.27	1	32.29		2.65
	II			31.35	78.21	0.63	31.30		2.1
C (A/C and Fans)	I	8	Mean	29.97	50.98	0.39	26.39	-0.13	0.69
	II	8		29.45	56.78	0.33	26.74	-0.25	0.71
	I		Min	28	47.26	0.08	24.57		-0.08
	II			27.11	48.81	0.11	21. 73		-1.26
	I		Max	31.01	59.91	0.75	29.56		1.78
	II			31.3	70.11	0.78	28.80		1.39
C (Fans, windows and/or doors opened)	I	18	Mean	31.85	62.25	0.33	28.80	0.82	1.49
	II	16		31.6	70.21	0.36	29.53	1	1.56
	I		Min	28.84	46.63	0.13	24.68		0.05
	II			29.13	62.89	0.12	24.46		-0.07
	I		Max	34.43	72.5	0.77	32.37		2.78
	II			33.7	75	1.13	34.41		3

PMV values differed from AMV data for SR and C houses which is consistent with earlier research findings [5]. The difference in AMV and PMV values between SR and C houses can be explained by the variation in survey time, clothing range 0.15clo-0.54clo, and in age of respondents (Table 2). Mean SET values in SR and C houses were above neutral [16], except 24.74°C SET in the build-up survey for SR houses with air-conditioned rooms. According to survey participants felt slightly cool at SET of 27.21°C, while according to Auliciems and Szokolay [16] this temperature value is in the range of 'slightly warm' and 'warm' sensations. Regression analysis of PMV, SET and AMV returned correlation coefficient of 0.21 for PMV, and 0.24 for SET.

Thermal sensation votes in SR houses were evenly distributed between temperature ranges (27-29°C, 29.01-31°C, and 31.01-34.43°C) as shown on psychrometric chart (Fig.1a), with 34% voting for 'neither cool nor warm' sensation and 35% voting for 'slightly warm'. The majority of votes (54%) in C houses were between 31.01-34.43°C; 32% of votes were distributed equally between 'warm' and 'slightly warm' sensations. During the build-up, 38.7% of participants felt 'neither cool nor warm'; 32% of participants in SR houses who felt 'neither cool nor warm' were satisfied and only 19% indicated 'no change' preference. In C houses, 20% of participants felt 'neither cool nor warm'; 15% were satisfied with thermal conditions; and 10% indicated 'no change' preference. During the wet, 29% of participants in SR houses felt 'neither cool nor warm' sensations; 17% were satisfied and had 'no change' preference (Fig.1b). In C houses, 25% of participants were satisfied with 'neither cool nor warm' thermal sensations, and 15% indicated 'no change' preference. The percentage of participants who indicated they would prefer cooler conditions increased by 10% with every 1K increase in air temperature over 29°C.

The majority of participants (67% in the build-up and 70% in the wet) who voted for 'slightly humid' or 'humid' or 'very humid' conditions, preferred less humid conditions during both surveys. However, in SR houses the percentage of participants dissatisfied with humidity levels increased from 31% in the build-up to 50% in the wet; in C houses the percentage of dissatisfied participants increased from 40% to 45%.

Air movement satisfied the majority of participants in both SR and C houses. However, in SR houses 21% of participants preferred more air movement in the build-up compared to 30% in the wet. More participants in C houses preferred more air movement, 37% during the build-up, and 40% during the wet.

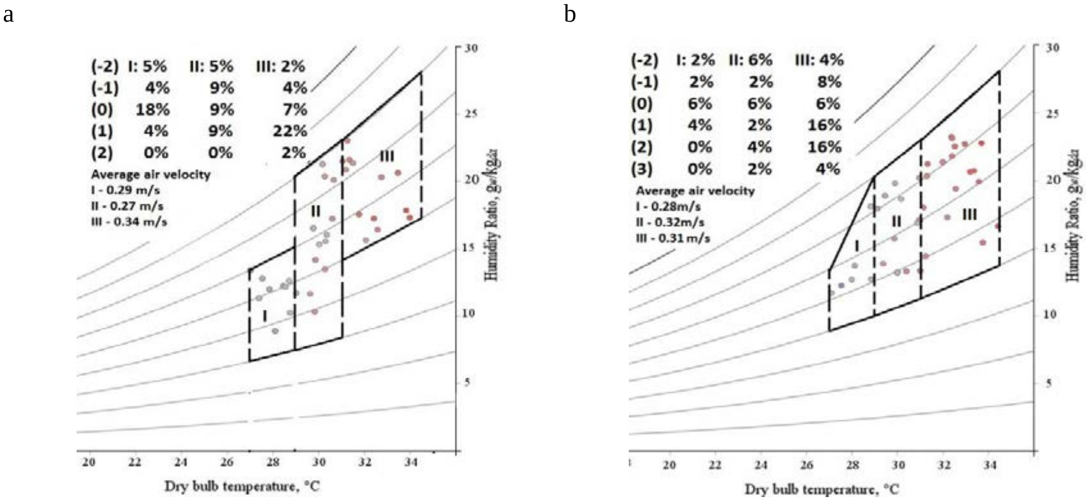

Fig.1. Distribution of indoor climatic measurements and votes in both surveys: (a) SR houses; (b) C houses.

3.2. Behavioural adjustment

During surveys, participants were asked how frequently they prefer to use air conditioner, fans, open windows, and/or open doors in the present thermal conditions. The majority of participants in both SR and C houses always use fans in the build-up and in the wet (Figure 2). In the build-up, 70% of participants in SR houses use air conditioners 'always' or 'often', as opposed to 40% in C houses. In the wet, 83% of participants use air conditioners 'always' and 'often' in SR houses and 40% in C houses. During the build-up, 35% in SR houses and 50% of participants in C houses 'always' use open windows. During the wet season, only 21% of participants 'always' open windows and 29% 'always' open doors in SR houses. However, the 'open windows' option in SR houses is likely to have been influenced by construction works being carried out in the Muirhead subdivision and complaints about dust entering the house through open windows and doors. All participants in SR and C houses indicated that they run air conditioners at night.

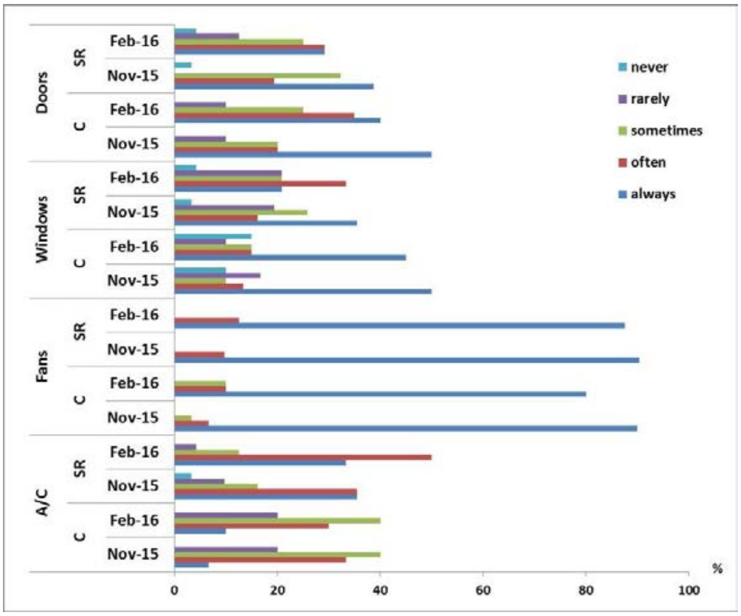

Fig.2. Frequency of utilization of air conditioner, fans, windows, and doors.

3.3. Indoor climatic conditions and energy consumption

Statistical summary of indoor climatic conditions presented in Table 4 is based on data collected from 7 December 2015 to 22 February 2016. Statistical summary of outdoor climatic conditions is based on BOM data for December 2015 and data collected for January and February 2016 from the weather station installed in Muirhead suburb. Data shows significant difference between mean monthly wind speed in December 2015 and January 2016 due to the difference in location of wind monitors, BOM wind monitor is situated in open space area as opposed to wind monitor in Muirhead situated in suburban area.

Nine SR and C houses participated in indoor climate measurements are single storey houses built with concrete blockwork wall on concrete slab on ground, have insulated colorbond roof and insulated ceiling, only C1 house is lightweight elevated house. Over the period of data collection, monthly mean air temperatures in living rooms of SR houses ranged from 28.58°C to 30.8°C. Monthly mean air temperature in living rooms in C houses ranged from 29.12°C to 31.59°C. Monthly mean relative humidity ranged from 49.9% to 73.8% in SR houses and from 69% to 81.5% in C houses. Monthly mean air velocity ranged from 0m/s to 0.21m/s in SR houses and from 0m/s to 0.28m/s in C houses (Table 4). Monthly mean half-hourly energy consumption ranged from 0.41kWh to 1.13kWh in SR houses and from 0.31kWh to 1.17 kWh in C houses.

The data analysis showed that 63% of data records in SR1 house in December 2015 and 59% in February 2016 were below 29.9°C and 70% relative humidity. The behavioural adjustment of respondents in the SR1 house was similar in the build-up and in the wet: often open windows and doors and always/often/often at night use air conditioner. SR3 house had 12% of data records in December 2015 and 8.5% in February 2016 below 29.9°C air temperature and 70% relative humidity. Among SR houses, SR3 house had the highest mean air temperature of 30.8°C in February 2016 and mean relative humidity of 73.8% in December 2015. During the build-up survey, SR3 occupants chose often use open windows/doors and always/often/sometimes air conditioner, while during the wet, the choice was often open windows and often/sometimes use air conditioner.

The C1 house had the lowest mean air temperature in living room among all C houses, the lowest mean half-hourly energy consumption, and the highest mean relative humidity among all SR and C houses. House C1 had only 19% of records below 29.9°C and 80% relative humidity, 7 records in December 2015 and 3 records in February 2016 with relative humidity below 70%. These data correlates with the choice of respondents rarely run air conditioner in the living room and always keep windows and doors open.

Houses SR2 and C5, with the highest mean half-hourly energy consumption, are households with young children. Mean values of internal thermal conditions in the living room of house SR2 in January and February 2016 were below 29.9°C and 60% relative humidity compared to 31.5°C and 70% in house C5. However, the mean half-hourly energy consumption of house SR2 was 0.05 kWh lower in January 2016 and 0.09 kWh higher in February 2016 than energy consumption of house C5. According to behavioural adjustment surveys, SR2 occupants never/rarely opened windows and doors and always utilised air conditioner in living room. While occupants in C5 always utilise windows, and only sometimes utilise air conditioner in living room.

Table 4. Half-hourly measurements of indoor climatic conditions in living rooms and energy consumption of 10 houses

House	T_{set}, °C		Dec-15 MEAN	SD	Jan-16 MEAN	SD	Feb-16 MEAN	SD
		Taout, °C	28.44	2.15	29.6	2.72	29.7	2.72
		RHout, %	78.65	11.28	77.5	10.67	78.9	10.24
		WindSpeed, m/s	3.54	1.75	1.6	0.83	1.86	0.88
SR1 6.4 star	23	Ta, °C	28.66	1.49	29.49	1.42	29.5	1.41
		RH, %	59.58	12.35	55.8	10.21	55.7	10.12
		Va, m/s	0.04	0.08	0.02	0.06	0.00	0.01
		Half hourly kWh	0.57	0.52	0.49	0.45	0.45	0.43
SR2 6 star	23	Ta, °C	30.71	1.77	29.08	2.26	28.58	1.63
		RH, %	67.72	8.04	51.74	10.87	49.9	7.74
		Va, m/s	0.0	0	0.06	0.09	0.02	0.06
		Half hourly kWh	0.47	0.63	1.12	0.75	1.13	0.63
SR3 6 star	26	Ta, °C	29.3	1.42	30.72	1.37	30.8	1.22
		RH, %	73.8	11.4	65.2	9.68	66.7	11.07
		Va, m/s	0.07	0.12	0.03	0.08	0.01	0.04
		Half hourly kWh	0.46	0.37	0.41	0.34	0.48	0.39
SR4 7 star	26	Ta, °C	29.7	1.45	30.31	1.53	30.3	1.38
		RH, %	69.6	10.24	59.8	10.01	62.9	10.67
		Va, m/s	0.00	0.09	0.00	0.01	0.00	0.05
		Half hourly kWh	0.50	0.68	0.65	0.77	0.67	0.82
SR5 6 star	26	Ta, °C	29.74	1.45	29.59	1.29	29.07	1.11
		RH, %	70.89	12.47	62.15	13.58	66.11	13.35
		Va, m/s	0.21	0.19	0.04	0.08	0.00	0.06
		Half- hourly kWh	0.41	0.33	0.53	0.35	0.50	0.32
C1	24	Ta, °C	29.12	1.64	29.9	1.54	29.6	1.45
		RH, %	79.3	7.46	77.3	6.54	81.5	5.87
		Va, m/s	0.08	0.16	0.15	1.5	0.19	0.16
		Half hourly kWh	0.37	0.34	0.38	0.38	0.33	0.33
C2	-	Ta, °C	29.3	1.06	30.6	0.99	30.0	0.90
		RH, %	74.5	10.5	71.6	5.06	75.4	5.36

House	T_{set}, °C		Dec-15 MEAN	SD	Jan-16 MEAN	SD	Feb-16 MEAN	SD
C2		Va, m/s	0.0	0.04	-	-	-	
		Half hourly kWh	0.65	0.47	0.47	0.41	0.62	0.44
C3 5.5 star	23	Ta, °C	30.5	0.89	31.59	0.91	31.12	0.89
		RH, %	73.6	6.53	69.4	4.3	72.0	4.08
		Va, m/s	0.10	0.19	0.14	0.19	0.17	0.24
		Half hourly kWh	0.61	0.58	0.62	0.46	0.74	0.46
C4	-	Ta, °C	30.6	1.09	31.19	0.99	31.0	0.96
		RH, %	72.8	5.16	70.7	4.48	73.2	4.42
		Va, m/s	0.00	0.01	0.02	0.06	0.01	0.06
		Half hourly kWh	0.31	0.24	0.47	0.30	0.51	0.36
C5	26	Ta, °C	30.7	1.25	31.55	0.72	31.47	0.79
		RH, %	71.9	6.73	69.0	3.32	70.6	4.04
		Va, m/s	0.25	0.16	0.25	0.15	0.28	0.17
		Half hourly kWh	1	0.48	1.17	0.42	1.04	0.37

3.1. Energy consumption

Average half-hourly energy consumption of SR houses increased from 0.58 in December 2015 to 0.72 in February 2016. Average energy consumption of C houses showed small variation over three months. Average monthly energy consumption in SR houses was 53-194.6kWh lower than average monthly consumption in C houses. High variation in December 2015 might be the result of end year holidays that changed usual pattern of energy consumption.

Table 5. Average half-hourly and monthly energy consumption, December 2015-February 2016

	Average half hourly, kWh			Average monthly, kWh		
	DEC2015	JAN2016	FEB2016	DEC2015	JAN2016	FEB2016
SR houses	0.58	0.64	0.72	846.34	953.57	995
C houses	0.72	0.76	0.75	1041	1116.1	1048

According to NatHERS regulations, 6 star rated houses in climate1 should have a maximum cooling load of 349 MJ/m^2/year (96.94kWh/m^2/year), that is in average 8kWh/m^2/month. Considering that coefficient of performance (COP) of modern air-conditioners ranges from 2 to 5, the input power required for this cooling load can range from 1.6 to 4kWh//m^2/month. This study had access to total energy consumption consumed by all appliances only. Therefore, average monthly energy consumption per square meter of conditioned area was analysed. Average monthly energy consumption in SR houses was 6.78-7.96kWh/m^2. SR houses consumed less energy per square meter during off-peak compared to peak time in January and February 2016. Average monthly energy consumption in C houses ranged from 7.86kWh/m^2/month to 8.58 kWh/m^2/month and was slightly higher during off-peak time in all three months.

4. Conclusion

This paper investigated the post-occupancy thermal performance of 6-7 star rated houses in hot and humid tropical conditions of Darwin, with comparison made to houses built before introduction of BCA 2009 requirements for thermal performance of detached houses. Thermal sensation surveys of participants showed that 37% in 6-7 star rated houses and 54% of observations in control houses were within the 31-34.43°C air temperature range, that is above the range stated as thermally comfortable in other studies [5-8]. Mean thermal sensation vote in the build-up and wet seasons for thermal sensation in air-conditioned rooms was between 'slightly cool' and 'neither cool nor warm' for SR houses and 'neither cool nor warm' for C houses. Mean thermal sensation vote in naturally and fan ventilated living rooms was in the range of 'slightly warm' sensation for SR houses and between 'slightly warm' and 'warm' sensations for C houses.

Thermal preferences and behavioural adjustment of occupants, house design, and built environment have impact on indoor climatic conditions. However, behavioural adjustment of occupants did not show an impact on energy consumption of households with high number of members. Average monthly energy consumption of households in 6-7 star rated houses was lower than household consumption in control houses across three-month study period. However, this study is based only on a three-month period. Ongoing measurements will enable a better understanding of thermal performance of 6 star and higher rated houses during other seasons of Darwin's tropical climate.

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