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Thermal Comfort in Public Housing Estates in High-density Cities under Near-extreme Summer Conditions

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Abstract: In Hong Kong, over 40% of the population reside in public housing estates and the majority of the occupants are elderly and people with disabilities, making them more vulnerable to extreme hot weather. Under near-extreme summer conditions, the poor conditions of thermal comfort is accentuated due to the high air temperature and exposure of solar radiation. The objectives of the present study is to examine the thermal comfort conditions in two common types of buildings in public housing estates in Hong Kong under typical and near-extreme summer conditions. Numerical modelling was used to obtain information about the PMV values and air temperature in the units of the two dwelling types. Results suggested that the level of thermal comfort varies across these two types of buildings. It was found that the more recent building type (Harmony) generally provides better thermal comfort in dwellings. It also exhibits smaller increase in thermal discomfort under near-extreme summer conditions in terms of maximum PMV values recorded. Further work will focus on identifying design parameters that are potentially influential to thermal comfort and the corresponding effect on energy consumption under different meteorological conditions, which will be incorporated into design recommendations in subsequent stage of the study.

Keywords: Thermal comfort, high-density cities, near-extreme summer, summer reference year

Introduction

The compact living environment in high-density cities leads to deteriorating living quality and significantly affects the health and well-being of building occupants. Reduced ventilation in high-density urban environment was found to be associated with the transmission and spread of infectious diseases (Li et al., 2007). Cramped environment also causes thermal discomfort (Cheng and Ng, 2006), noise annoyance (Kang, 2001), and psychological stress (Kaplan, 2001).

Thermal comfort of indoor environment is particularly important to building occupants since overheating in buildings causes heat stress and even deaths if heat is accumulated (Roaf et al., 2009). The 2003 heatwave in Europe is one of the examples of how prolonged intense heat causes deaths in buildings (D'Ippoliti et al., 2010).

Under future climate change, the frequency, magnitude and duration of such intense heat is likely to increase, particularly in urban areas where urban heat island phenomenon exacerbates the impact of intense heat. In order to assess the thermal comfort conditions of indoor environment, a near-extreme meteorological data set, namely Summer Reference Year (SRY), was developed for the assessment of building environmental performance (Jentsch et al., 2015). Unlike Test Reference Year (TRY) and Typical Meteorological Year (TMY) which represent typical year conditions, the SRY represent the near-extreme summer conditions in the multi-year series, especially in sub-tropical climate where overheating is very common in buildings due to high temperature (Lau et al., 2017). It provides a dataset for estimating summer discomfort in naturally ventilated and free-running buildings.

In Hong Kong, over 40% of the populations reside in public housing estates with mostly vulnerable groups to extreme hot weather such as elderly, physically disabled, socially or economically deprived. While mechanical cooling is relatively common in Hong Kong, the high cost incurred still prevents them from using it to relieve the intense heat during extreme hot weather. As such, the design of residential units is of utmost importance for providing natural ventilation and improving thermal comfort.

The present study aims to employ the SRY meteorological data set to examine the thermal comfort conditions in two dwelling types of public housing estates in Hong Kong. Numerical modelling was used to obtain information about the indoor environmental conditions in the units of the two dwelling types. The effect of unit orientations is also discussed for these two dwelling types. Temporal variations in thermal comfort conditions are also investigated. Findings of the present study contribute to a better understanding of thermal comfort under near-extreme summer conditions and the identification of key design parameters for subsequent parametric study.

Methodology

Building Types

Two common building types were selected for the present study. Trident (Figure 1, left) is a common building type in public housing estates in the mid-1980s to the early 1990s. It is characterised by the Y-shape building form and typically up to 35 storeys. There are generally 18 - 24 units per storey with a size of 32 - 44 m^2. Harmony (Figure 1, right) emerged as a successor to Trident and it was still adopted in recent development of public housing estates. It generally has over 40 storeys with 16 - 18 units per storey. The unit size ranges from 16 - 51 m^2. Both represent the typical high-density residential environment in Hong Kong.

Experimental Setup

Numerical simulation was performed using DesignBuilder v5, in which indoor environmental conditions were generated by the dynamic EnergyPlus v8.5 simulation engine. Generic models of the units were constructed in block level and further partitioned into zones with different activities allocated accordingly (Figure 2). Full-size windows without fitted air-conditioners or exhaust fans were carefully placed at a height of 1.8m based on the floor layout plans. Component blocks were then added on top of windows where the flat above extrudes for providing shading. To reduce the computational cost, only flats of the mid or top floors for each building type were constructed in detail, while the common areas and the rest of the building were represented by a single adiabatic component block.

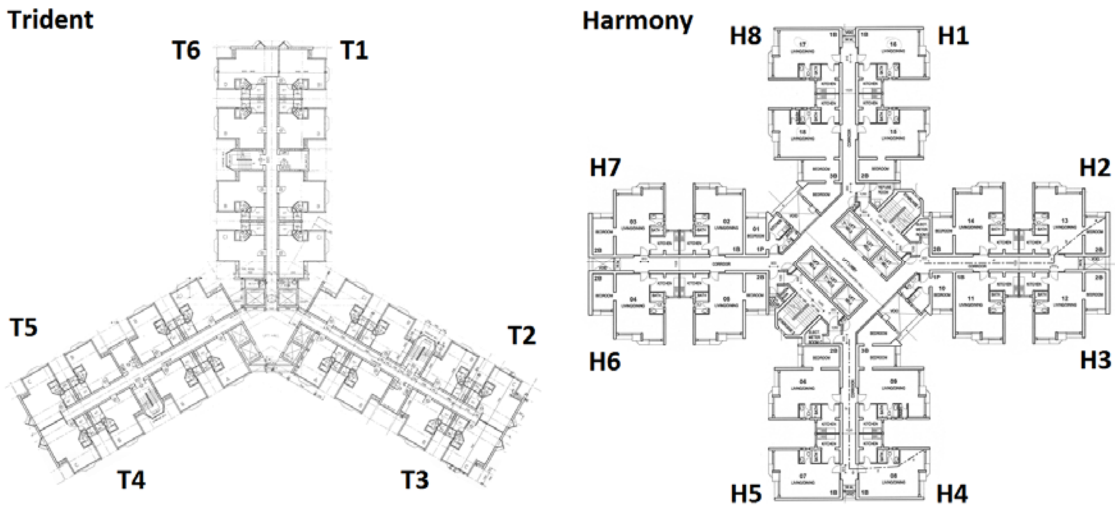

Figure 1. Building layout of Trident (left) and Harmony (right) types in public housing estates in Hong Kong.

The physical parameters of the modelled units were specified for the two building types in order to produce more accurate and realistic results. Construction materials were also determined according to current literature and practice (Table 1). Occupant density was assumed to be 0.083 person/m^2 based on the average living space per person of $12m^2$ (Housing Authority, 2016). Simulations were set as free-running for each building type. No mechanical ventilation was applied and windows were assumed to remain open for 30% of the time.

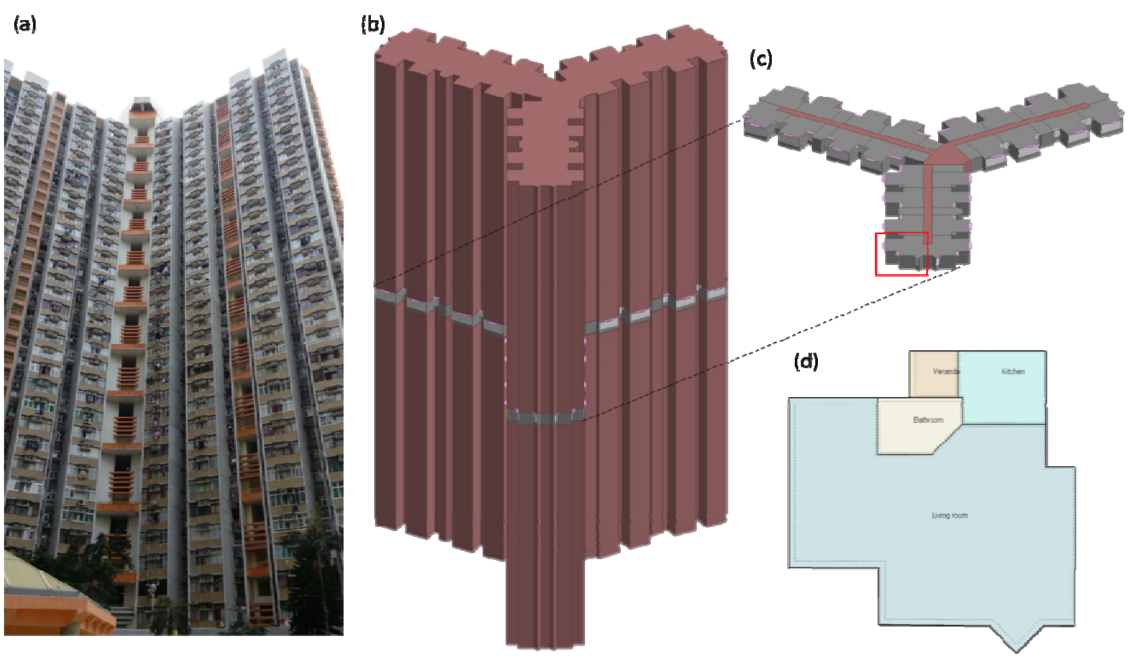

Figure 2. (a) On Chiu House (Trident type) in Cheung On Estate and generic models of (b) the whole building, (c) mid-floor flats and (d) a partitioned flat constructed in DesignBuilder.

Typical meteorological conditions are represented by using Test Reference Year (TRY; Levermore and Parkinson, 2006). The TRY of the Chartered Institution of Building Services Engineers (CIBSE) is composed of the most “typical” months from a meteorological dataset of at least 20 years. Near-extreme meteorological data representing critical summer conditions were used as the input meteorological conditions in the present study. Lau et al. (2017) utilised the SRY approach to develop a near-extreme summer meteorological data set for Hong Kong, consisting of meteorological data from April to September. Hourly outputs for summer months (June to August) were extracted and analysed for the thermal comfort conditions in different building types.

Table 1. The properties of building physical parameters, construction materials used in the present study.

	Trident		Harmony
Building physical parameters			
Floor height (m)		2.7	
Total occupied floor area (m^2)	920.6		670.5
Cooled area (i.e. living room, bedroom) (m^2)	731.2		506.2
Window-to-wall ratio	0.305		0,167
Building construction			
External wall (outside to inside): U-value (W m^{-2} K^{-1})	3.33		2.88
- Mosaic Tile (mm)		5	
- Concrete Gypsum Plasterboard (mm)		10	
- Concrete (mm)	135		235
- Gypsum Plastering (mm)		13	
- Thermal conductivity (W m^{-1} K^{-1})	0.532		0.749
Roof: U-value (W m^{-2} K^{-1})		0.58	
- Asphalt Mastic Roofing (mm)		20	
- Expanded Polystyrene (mm)		50	
- Reinforced Concrete (mm)		200	
- Gypsum Plasterboard (mm)		13	
- Thermal conductivity (W m^{-1} K^{-1})		0.164	
Internal partition: U-value (W m^{-2} K^{-1})		2.86	
- Gypsum Plasterboard (mm)		10	
- Concrete (mm)		80	
- Gypsum Plasterboard (mm)		10	
- Thermal conductivity (W m^{-1} K^{-1})		0.286	
Floor slab: U-value (W m^{-2} K^{-1})		2.48	
- Floor Tiles (mm)		10	
- Reinforced Concrete (mm)		180	
- Gypsum Plasterboard (mm)		10	
- Thermal conductivity (W m^{-1} K^{-1})		0.495	
Glazing: U-value (W m^{-2} K^{-1})		5.75	
- Clear Float Glass (mm)		6	

Indoor Thermal Comfort

Indoor thermal comfort of the modelled units is described by air temperature (Ta) and Predicted Mean Vote (PMV; Fanger, 1972). Cheng and Ng (2006) defined the maximum acceptable air temperature as 29.5°C for naturally ventilated buildings during summer in

Hong Kong. The PMV model uses a seven-point scale from -3 to +3 to represent human thermal sensations from cold to hot. In accordance with the ISO7730, the calculation of PMV assumes a metabolic rate of 0.9 met and a clothing index of 0.3 clo in this study.

Results and Discussion

Thermal Comfort in the Two Types of Buildings

Figure 3 shows the summer mean PMV in the two building types modelled in the present study. In general, the PMV values of Trident are higher than those of Harmony, primarily due to the higher U-value of Trident units allowing faster heat transmittance. For Trident, the east- and west-facing façades show higher PMV values than the rest, slightly tilted orientations using both TRY and SRY data set. The corresponding values for the east- and west-facing façades under near-extreme summer conditions (SRY) are 1.78 and 1.70 respectively. The west-facing façade exhibits lower increase in maximum PMV shown by the difference between TRY and SRY data, particularly in the northwest-facing façade with an increase of 0.3 in maximum PMV value. It suggests that diagonally orientated, north-facing façades are able to reduce the discomfort under near-extreme summer conditions. Self-shading by the building itself is one of the important design strategies to minimize radiant heat gain and better design of site layout also contributes to the reduction of exposure to solar radiation.

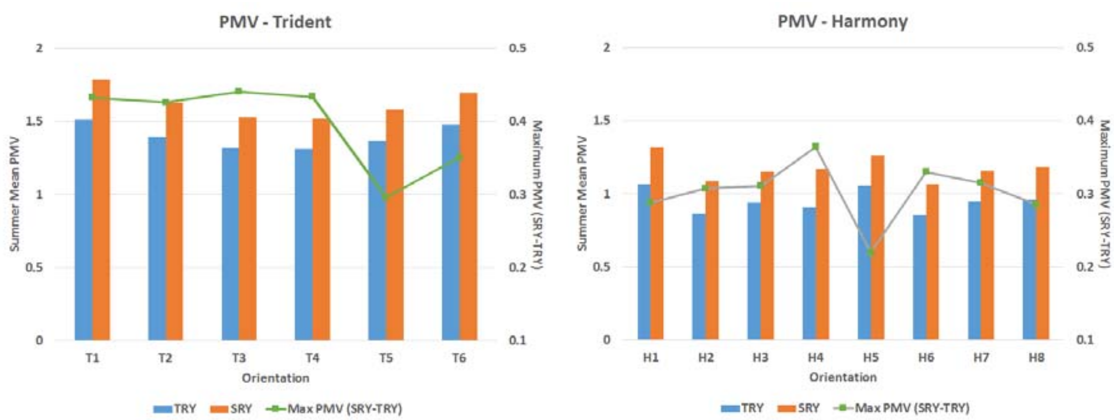

Figure 3. Summer mean PMV of different orientations for Trident (left) and Harmony (right) using TRY and SRY data. Line graph shows the difference in PMV between TRY and SRY.

Indoor air temperature was extracted to examine the overheating conditions of the modelled units. Table 2 shows the daily maximum indoor temperature (T_{max}) in different orientations of the Trident units. It clearly shows that the east- (T1) and west-facing (T6) façades exhibit higher T_{max}, which is up to near 1°C higher than the south-facing units in July under the typical (TRY) scenario. Solar altitude is relatively lower when these units were sunlit so the level of solar radiation is more intense, resulting in higher thermal load in the units. Moreover, the highest increase in T_{max} under the near-extreme (SRY) scenario was observed in west-facing units (about 1.6°C higher than the TRY scenario. It implies that design features should be oriented to reducing the absorption of solar heat in these units.

Indoor T_{max} observed in the Harmony units is generally smaller than that in the Trident units. The differences between east- and west-facing units and other orientations are smaller in Harmony units (Table 3), suggesting that new design of public housing creates a less variable indoor environment. The effect of near-extreme conditions is more prominent in August, with increase in indoor T_{max} ranging from 1.3-1.5°C. In addition, in both building types, indoor T_{max} under near-extreme summer conditions exceeds the threshold of very hot day warning issued by the Hong Kong Observatory (Hong Kong Observatory, 2016). It indicates potential heat stress experienced by building occupants under such overheating conditions.

Table 2. Daily maximum indoor temperature in the six orientations of Trident units during summer months.

	Month	T1	T2	T3	T4	T5	T6
	June	33.38	33.13	32.91	32.93	33.31	33.63
TRY	July	33.46	33.10	32.76	32.75	33.13	33.61
	August	33.14	32.90	32.70	32.68	32.73	33.18
	June	34.47	34.12	33.72	33.76	34.27	34.69
SRY	July	34.40	34.17	33.85	33.85	34.55	35.05
	August	34.38	34.19	34.00	33.96	34.25	34.74

Table 3. Daily maximum indoor temperature in the six orientations of Harmony units during summer months.

	Month	H1	H2	H3	H4	H5	H6	H7	H8
	June	32.25	31.83	31.78	32.07	32.37	31.77	31.89	32.32
TRY	July	32.46	31.99	31.98	32.28	32.72	31.95	32.04	32.53
	August	31.94	31.53	31.57	31.93	32.08	31.52	31.55	31.94
	June	33.40	32.83	32.81	33.50	33.32	32.72	32.78	33.33
SRY	July	33.28	32.72	32.69	33.10	33.41	32.65	32.74	33.47
	August	33.08	32.82	32.83	33.05	33.40	32.82	32.88	33.40

Diurnal Variation of Indoor Air Temperature in Two Buildings

It was found that the orientation differs in the diurnal variation of indoor air temperature (Figure 4). For Trident units, east- and west-facing façades show higher indoor temperature than the rest of the façades with a diurnal range of about 2.4°C. Due to the high thermal conductivity of the Trident buildings, indoor temperature increases at a higher rate from sunrise to late-afternoon. Moreover, the east-facing unit exhibits higher indoor temperature (about 0.5°C) in the morning due to the exposure to solar radiation at low solar altitude.

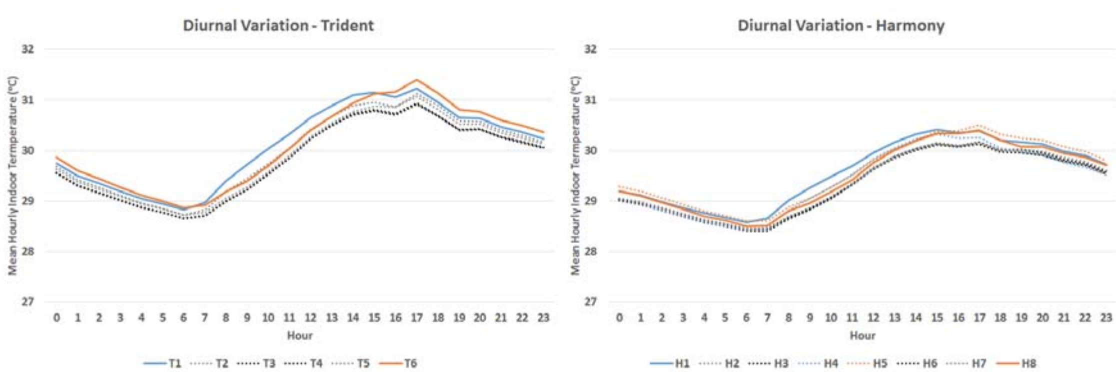

Figure 4. Mean indoor temperature for individual hours for Trident (left) and Harmony (right) using SRY data.

Despite of the lower indoor temperature observed in Harmony units, the diurnal range is lower with the maximum diurnal range (1.9°C) found in the west-facing unit (H8). Similar diurnal pattern is observed in Harmony units. As one of the west-facing units (H5) is relatively unobstructed in the afternoon, higher indoor temperature is observed from mid-afternoon to late evening. It suggests that the accumulated heat stored in the unit and retained throughout the night, resulting in potential heat stress during night-time.

Further Work

The present study compares the level of thermal comfort in two common types of public housing in Hong Kong under typical and near-extreme summer conditions which were represented by TRY and SRY respectively. Numerical modelling was used to obtain information about the PMV values and air temperature in the units of the two dwelling types. It was found that the more recent building type (Harmony) generally provides better thermal comfort in dwellings. It also exhibits smaller increase in thermal discomfort under near-extreme summer conditions in terms of maximum PMV values recorded. Higher PMV values were observed in east- and west-facing units and the west-facing units also showed higher maximum air temperature due to the combined effect of high air temperature in the afternoon and direct sun exposure. Due to the difference in insulation, the Harmony units have a smaller diurnal range of indoor air temperature which provides more stable indoor environmental conditions and better thermal comfort.

Further work will focus on identifying parameters that are potentially influential to thermal comfort and the corresponding effect on energy consumption under different meteorological conditions. Design features will also be identified and findings will be incorporated into future design of public housing which accommodates the majority of population in Hong Kong. Parametric studies will therefore be conducted to examine the sensitivity of different design parameters and determine the extent of how they affect thermal comfort conditions.

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