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A comparative study on the indoor thermal comfort and energy consumption of typical public rental housing types under near-extreme summer conditions in Hong Kong

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Abstract

Residents of the dense urban environment in Hong Kong suffer from poor living conditions due to building overheating, especially during near-extreme summer conditions. In this study, the thermal comfort and energy performance of typical public rental housing (PRH) building types were simulated using DesignBuilder. Results show that the oldest Slab type PRH, which has a compact building form, has the highest indoor air temperature, yet the lowest cooling energy demand. On the other hand, the Trident type PRH, with the largest external wall U-value, performs the worst overall and is the most responsive to outdoor temperature changes.

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Keywords: Building simulation; thermal comfort; energy performance; summer reference year (SRY); Hong Kong public rental housing

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1. Introduction

Buildings account for 90% of the total electricity consumption in Hong Kong [1]. As concerns regarding environmental and health problems caused by the urban built environment increase, the evaluation of building performance, reflected by aspects like thermal comfort and energy usage, becomes crucial for the sustainable development of cities. A common evaluation approach is to make use of commercially available simulation tools such as EnergyPlus [2]. The typical meteorological year (TMY) hourly weather data developed by Chan et al. [3] has often been used previously for energy simulation studies in Hong Kong [4,5]. However, the TMY may be inadequate to assess the performance of buildings under onerous warm weather conditions as a result of climate change. Therefore, to better represent such near-extreme summer conditions in simulations, the concept of Summer Reference Year (SRY) was introduced [6]. A set of SRY weather data has also been recently derived for Hong Kong [7].

Hong Kong has a subtropical climate and is unique for its high-density urban environment. During the hot and humid summers, overheating is common in buildings due to high air temperature, intense solar radiation and poor ventilation. This leads to thermal discomfort, a greater energy demand for mechanical cooling [8], as well as a higher heat-related mortality rate [9]. Public rental housing (PRH) accommodates nearly half of the population in Hong Kong [10], of which most are elderly, physically disabled or financially less capable, making them particularly vulnerable to extreme hot weather. To ameliorate the indoor thermal discomfort, air conditioners are extensively used to cool flats; this, however, incurs high costs and may not be affordable for all. Hence, PRH flats under free-running conditions should also be considered in building simulations.

This study aims to assess and compare the indoor thermal comfort and cooling energy consumption of four typical PRH building types in Hong Kong under near-extreme summer conditions. A simple discussion on how building design might have an effect on building performance will also be presented.

2. Methodology

The four typical PRH building types chosen for this study are namely Slab, Trident, Harmony and Concord (Figure 1). They possess distinctive building forms and represent different generations of PRH designs from the 1970s through to the 2000s, with Slab type PRH being the oldest, and Harmony and Concord types more prevalent amongst newer PRH estates.

Building simulations were set up with the DesignBuilder v5 software, in which building performance data were generated using the dynamic EnergyPlus v8.5 simulation engine. To reduce the computational cost required, only the floor in the middle of the high-rise building was simulated to represent the average scenario of each building type [11]; the rest of the building was constructed as a single adiabatic component block. Flats were first constructed in block level and then further partitioned into zones with different activities allocated accordingly. Windows were fitted based on the floor layout plans and, unless otherwise specified, were assumed to have a height of 1.8m. Component blocks were added on top of windows where the flat above extrudes to provide shading. Further details on the building model properties [11-13] are presented in Table 1. Although occupants in different PRH estates may vary in household sizes and demographic backgrounds, a uniform occupant density of 0.83 people/m^2 [10] was adopted for all four building types for a fairer comparison of the building design itself.

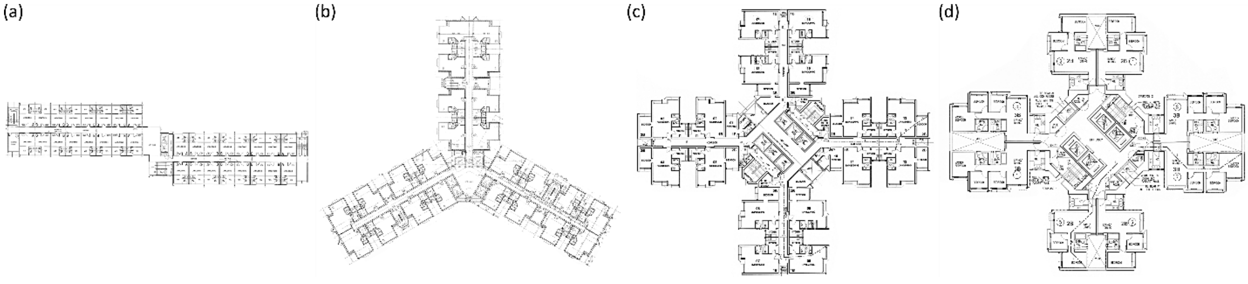


Figure 1. Layout plans of the (a) Slab, (b) Trident, (c) Harmony and (d) Concord type PRH in Hong Kong.

Table 1. Building physical parameters, construction materials and their properties used in the simulations.

	Slab	Trident	Harmony	Concord
Building physical parameters				
Floor height (m)	2.6	2.7	2.7	2.75
Total occupied floor area (m^2)	842.5	920.6	670.5	325.1
Cooled area (i.e. living room, bedroom) (m^2)	555.4	731.2	506.2	256.8
Building model construction				
External wall (outside to inside)				
U-value ($W\ m^{-2}\ K^{-1}$)	3.13	3.33	2.88	2.75
- Mosaic Tile (mm)	5			
- Concrete Gypsum Plasterboard (mm)	10			
- Concrete (mm)	175	135	235	272
- Gypsum Plastering (mm)	13			
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			
Glazing				
U-value ($W\ m^{-2}\ K^{-1}$)	5.75			
- Clear Float Glass (mm)	6			

Simulations were run using two different heating, ventilation and air conditioning (HVAC) settings: 24-7 calculated natural ventilation and scheduled air-conditioning (cooling only). For naturally ventilated flats, no mechanical ventilation was applied and windows were assumed to remain 30% open regardless of the outdoor weather conditions. For air-conditioned flats, overnight cooling, from 2pm to 8am [11] at a setpoint temperature of 25°C, was applied to bedrooms and living rooms only. A coefficient of power of 2.5 was adopted for the air conditioning system [14].

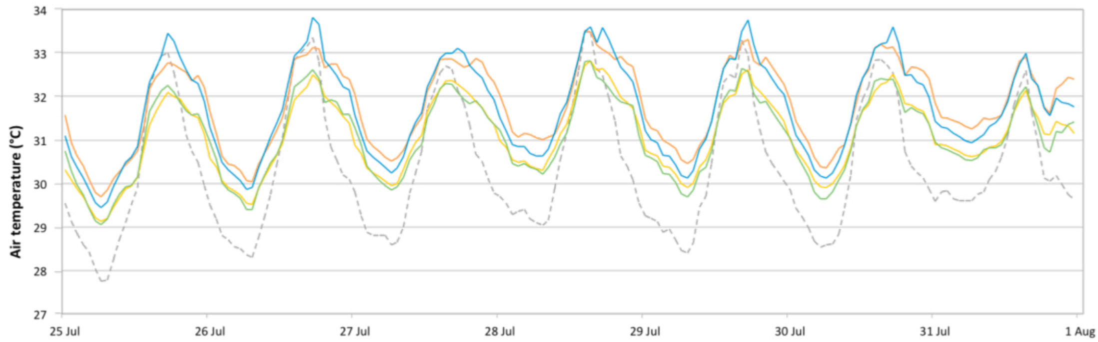
3. Results and discussion

Simulations were run using the SRY weather file of Hong Kong [7] for the whole summer (May – September), during which a prolonged hot period is observed from 25 to 31 July. The daily minimum outdoor temperatures of the selected week remain above 28°C for six consecutive days and the daily maximum temperatures exceed 33°C during four out of the seven days (Figure 2). The Hong Kong Observatory defines these conditions as hot nights and hot days, respectively, and a Very Hot Weather Warning has been introduced to alert citizens to the potential health risks and to advise the public on preventive measures [15]. As extreme weather events are expected to be more frequent due to climate change, it is particularly important to understand the indoor thermal comfort and energy performance of buildings during potential heat waves in high-density cities. Therefore, this paper will focus on evaluating the indoor air temperatures and cooling energy consumption of the four PRH types during this week of severely hot weather.

3.1. Indoor air temperature

The simulated indoor air temperatures of the four PRH types under free-running conditions are shown in Figure 2. Overall, higher temperatures are observed for Slab and Trident types PRH throughout the studied period, with the former having the highest median and minimum temperatures of 31.8°C and 29.69°C. However, during the hottest hours of the day, indoor air temperatures are the highest for Trident type PRH. It is also worth noting that its indoor air temperature does not fall below the outdoor temperature at any time during the period, while the other PRH types have up to seven hours cooler than outdoor conditions during the day. During the night, all PRH types are significantly warmer indoors as heat gain during the day is retained within the flats. The indoor-outdoor temperature differences are around 2°C for Slab, 1.5°C for Trident, and 1°C for Harmony and Concord types PRH.

Indoor air temperatures are plotted against outdoor air temperatures to show the responses of buildings to changes in outdoor temperatures (Figure 3). A linear relationship is seen for all four PRH types, in agreement with the previous



Temperature (°C)	Outdoor	Slab	Trident	Harmony	Concord
Maximum	33.48	33.52	33.81	32.82	32.81
Median	30.10	31.80	31.64	31.12	31.01
Minimum	27.75	29.69	29.44	29.13	29.05

Figure 2. Outdoor air temperatures and simulated indoor air temperatures for the four PRH types under free-running conditions from 25 to 31 July. The maximum, median and minimum temperatures are highlighted for easier comparison.

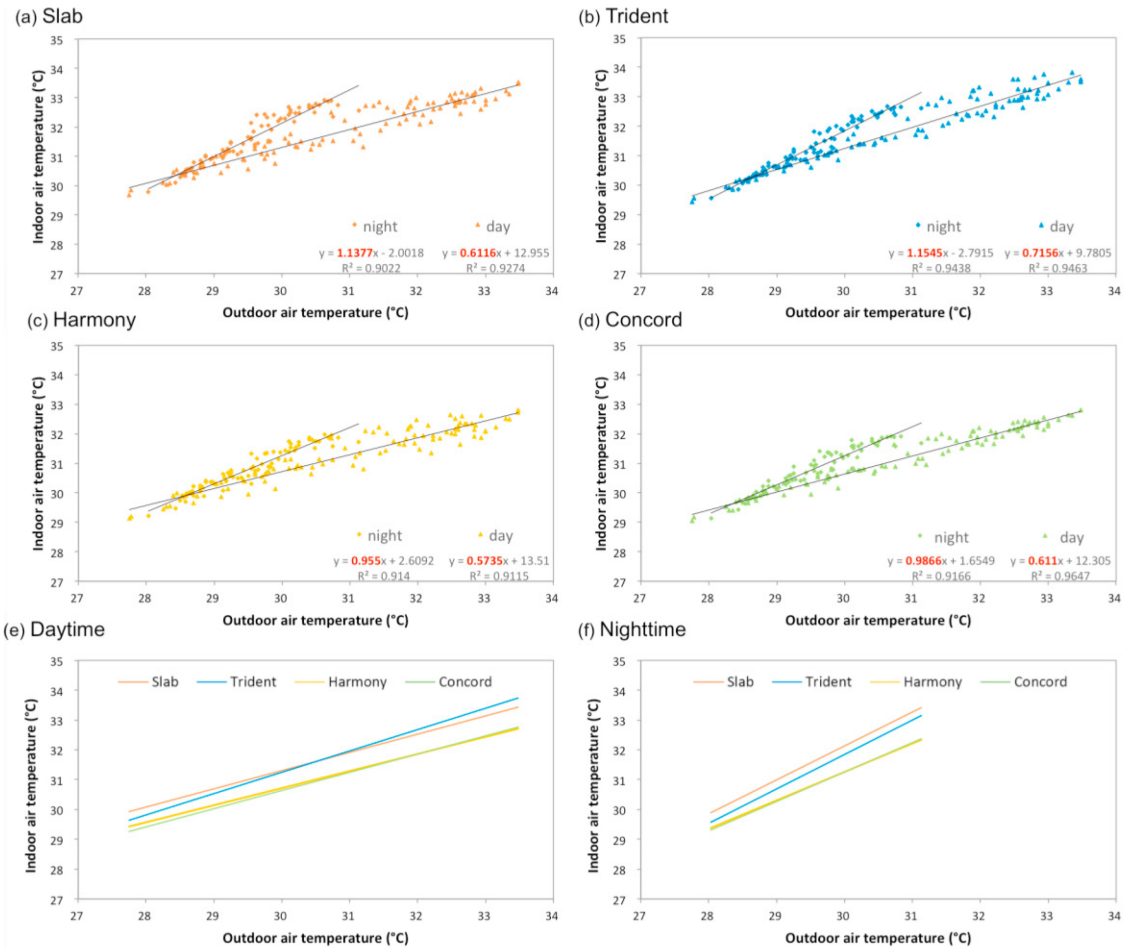


Figure 3. Simulated indoor air temperatures against outdoor air temperatures for (a) Slab, (b) Trident, (c) Harmony and (d) Concord types PRH. Comparisons of the responses of buildings to changes in outdoor temperatures during (e) daytime and (f) nighttime.

findings of Coley and Kershaw [16]. The data are further analysed to show a more sensitive response, indicated by a steeper gradient, for all four PRH types during nighttime (8pm-6am). Trident type PRH shows the most pronounced response, while Harmony type PRH is the least sensitive to external temperature changes during both daytime and nighttime (Figures 3e and f). As urban built environments suffer from increasingly high temperatures as a result of intensified urban heat island events [17], this parameter may become important for evaluating the resilience of a building under climate change.

3.2. Cooling energy consumption

Air conditioning is a common way to mitigate the high indoor temperatures in PRH flats during summer in Hong Kong. Figure 4 shows the simulated cooling energy demand during the selected hot week. To allow a fair comparison of the energy performance between different PRH types, the amount of electricity used for cooling is normalised by the total volume of cooled space, which excludes kitchens, bathrooms and balconies, of each PRH type (Table 1). Besides, all other HVAC options, including the setpoint temperature and cooling schedule, are uniformly set. Trident type PRH is found to have the highest total energy consumption of around 1280 Wh/m^3 during the studied period, closely followed by Concord type PRH. Although Slab type PRH is the hottest under free-running conditions, it requires the least amount of energy to maintain the set indoor temperature by mechanical cooling. On the contrary, Concord type PRH, which has the lowest indoor temperatures under free-running conditions, uses almost 40% more energy per m^3 than Slab type for cooling.

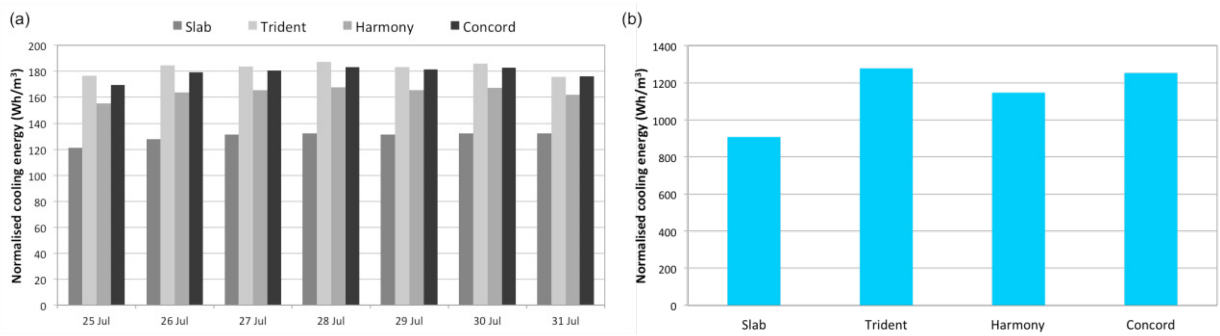


Figure 4. a) Daily and (b) total normalised cooling energy consumption for the four PRH types during the selected study period (25-31 July).

3.3. Correlations with building design

Taking into account its indoor air temperatures, response to outdoor temperatures, as well as energy performance, Trident type PRH appears to perform the worst during the week of severely hot weather. Trident type PRH also has the highest external wall U-value of 3.33 Wm^{-2}K^{-1} (Table 1). Harmony and Concord types PRH both have a cross-shaped building form (Figure 1), and they show largely similar variations in indoor air temperatures (Figures 2 and 3). The contrasting performance of Slab type PRH under free-running and mechanically cooled conditions may also be attributable to its unique compact building form (Figure 1). In light of these observations, a preliminary attempt to correlate building performance with building design has been made. However, a linear regression analysis is considered inappropriate here due to the limited data points.

A general positive correlation is found between the external wall U-values and the responses of buildings to changes in outdoor temperatures (Figure 5a). As the U-value measures the rate of heat transfer of a material, it is also reasonable for a building with more conductive external walls to reach a higher maximum indoor air temperature (Figure 5b). Lastly, Figure 5c shows that the cooling energy consumption may be related to the proportion of exposed cooled space. A noticeable feature of a Slab type PRH flat is the setback of its living room from the façade. A balcony serves as an indoor-outdoor space to modulate the indoor conditions of the living room. Hence, this may explain the lower cooling energy demand for Slab type PRH flats.

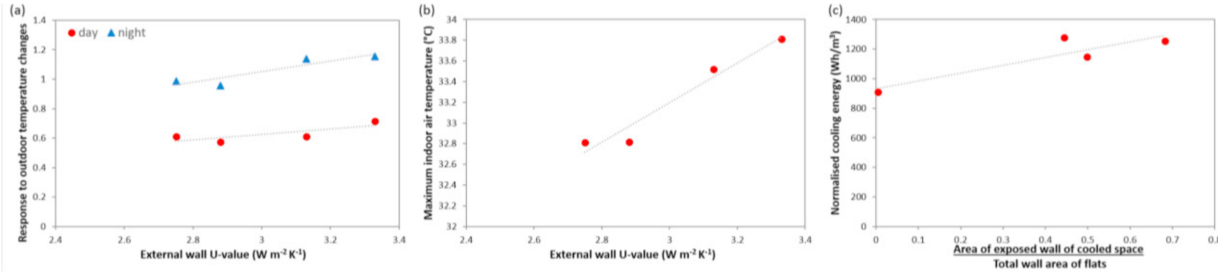


Figure 4. a) Daily and (b) total normalised cooling energy consumption for the four PRH types during the selected study period (25-31 July).

4. Conclusion

In this study, the indoor air temperatures and cooling energy consumption of the Slab, Trident, Harmony, and Concord types PRH in Hong Kong during a severely hot week have been evaluated. The older Slab and Trident types PRH are found to be generally hotter; the latter also requires the most energy for cooling and is the most responsive to changes in outdoor temperatures. Building features, such as the external wall U-value and the area of exposed walls, may have a direct effect on building performance. Therefore, to improve building performance and mitigate the poor living conditions in dense urban environments, it is advisable to define guidelines for building designs that provide better thermal comfort. However, more detailed parametric studies and analyses on other factors of thermal comfort, e.g. air speed and relative humidity, would be necessary to supplement the findings of this study.

Acknowledgements

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