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Thermal comfort improvement of naturally ventilated patient wards in Singapore

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ABSTRACT

Located near the equator, Singapore has a tropical rainforest climate with high temperature and high humidity. In hospitals of Singapore, the subsidized patient wards are designed to be naturally ventilated, considering the affordability for patients. However, due to the high occupant density of the patient wards and the hot humid climate, occupants may feel discomfort, especially in the older hospital wards which were not well designed for natural ventilation. In this paper, the thermal comfort level of occupants at Singapore's Changi General Hospital (CGH) is evaluated based on both in-situ measurements and modeling analysis. Against this backdrop, several low energy solution concepts that potentially improve the thermal comfort level of occupants in patient wards are analyzed and simulated using detailed building thermodynamic and airflow simulation. We found that this approach of combining thermodynamics, computational fluid dynamics, and thermal comfort level models was effective for analyzing and comparing the thermal comfort impact of alternative, low-energy building retrofit concepts. We also found that passive solutions to ventilation could be used effectively for a patient hospital ward, even in the tropical warm climate of Singapore.

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1. Introduction

There has been a significant increase in the global energy demand in the past few years, and buildings are one of the major contributors to this huge demand. It is shown in [1] that 48% of the total energy in the United States is consumed by buildings, mostly due to the extensive use of air conditioners (ACs). As such, considerable research efforts have been devoted to devising solutions to help reduce the use of ACs in buildings. For example, by designing naturally ventilated building space to improve the thermal comfort of building occupants [2]. However, most such studies have been conducted under temperate climates in European countries and other developed regions of the world, which give outcomes that cannot be transferred to a tropical country like Singapore.

Singapore is 1-degree north of the equator. It has a tropical rainforest climate which is characterized by relatively uniform temperature and pressure, high humidity, and abundant rainfall. The average monthly temperature, relative humidity and sunshine hours are shown in Fig. 1. The mean monthly temperature varies from 26 °C in December and January to 27.8 °C in May and June. The humidity is high, ranging from 82.6% to 86.7%. Monthly sunshine hours (with direct irradiation from the sun of at least 120 W/m^2) range from 129.6 h in November to 192.7 h in March. In Singapore, wind directions are mainly northerly to north-easterly during the Northeast Monsoon season (December to March) and southerly to south-easterly during the Southwest Monsoon season (June to September). Wind strength is greater during the Northeast Monsoon. The inter-monsoon months (April, May, October and November) are transition periods among the monsoons and show weaker and more variable winds.

To achieve thermal comfort of occupants, mechanical cooling has been widely installed in all types of buildings including residential, commercial, and industrial buildings. It was reported that electricity consumption for cooling accounts for 60% of total building electricity usage [4]. To build a sustainable environment, the Building and Construction Authority (BCA) of Singapore launched the Green Mark Scheme in 2005 to promote environmental awareness in the construction and real estate sectors. Natural ventilation is one of the promoted approaches in Green Mark to improve the energy efficiency of buildings. In a well-designed naturally ventilated building, no or very little energy is needed for cooling and/or ventilation. With this approach, thermal comfort is achieved through passive designs. While the potential demand for passive natural ventilation is high, the design of such systems is diffi-

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Nomenclature and Abbreviations

AMV	actual mean vote
BCA	Building and Construction Authority
CFD	computational fluid dynamics
CFFT	Complex Fast Fourier Transform
CGH	Changi General Hospital
CIBSE	Chartered Institution of Building Services Engineers
DSFs	Double Skin Facades
ECM	energy conservation measure
EPI	energy performance index
HDB	Housing and Development Board
IDC	SUTD-MIT International Design Centre
IES	Integrated Environmental Solutions
VE	virtual environment
WHO	World Health Organization
WSN	Wireless Sensor Network
ISO	International Organization for Standardization
IWEC	International Weather for Energy Calculations
NAP	night air purge
PMV	predicted mean vote
PPD	predicted percentage of dissatisfied
SUTD	Singapore University of Technology and Design
UHI	Urban Heat Islands

cult, primarily due to the need to ensure the thermal comfort of occupants. This is particularly true for existing buildings, where existing structures may inhibit the application of many passive design strategies. In this context, simulation and analysis of potential concepts become crucial to virtually simulate, test, and explore.

In this paper, we develop and explore this approach of combining thermal, airflow and comfort level simulation into a combined analysis of naturally ventilated retrofit design concepts for hospital patient wards. We find the approach efficient and effective for screening and comparing alternative retrofit concepts. The most commonly used passive design strategies for cooling in Singapore include building massing to allow for good ventilation, orientation to minimize heat gain, well-insulated building envelope systems, sun-shading devices, and vegetation, etc. However, those strategies are most applicable in the design phase of new building constructions. It is more difficult to improve thermal performance of existing buildings with fixed physical conditions using retrofitted passive cooling strategies.

However, there are passive cooling strategies that are potentially suitable for existing buildings as retrofits. These include thermal chimneys, night air purge, windcatchers, wind walls, active window shades, and reflective surfaces. These are technologies which can be installed onto and within existing structures. Their applicability to any given project varies due to the existing building layout, orientation, construction, and use. Due to the special features of hospital wards, the design of passive cooling strategies can be different from normal building types. The special features of hospital wards include:

(1) High occupant density so the cooling load is high and the thermal conditions can be severe.
(2) Large shared open spaces with few obstacles, implying potential alignment for good natural ventilation design.
(3) Different thermal comfort levels of patients and healthcare staff due to their different activities. Patients are lying down or seated most of the time so they have lower metabolic rate, while healthcare staff are walking around to take care of patients so they have higher metabolic rate.

For Singapore's Changi General Hospital (CGH) patient ward, three low energy strategies were considered. These are thermal chimneys, night air purge (NAP), and wing walls.

Thermal chimneys enhance the ventilation of a building through a stack effect, using the principle that hot air rises because it is at a lower density. When the building exhaust air is further heated in a solar heated dark chimney, it can thereby draw air from the building. The design of such systems is difficult, requiring careful zoning. In [5], a thermal chimney system was constructed to enhance the air ventilation within the interior spaces using a series of solar assisted ducts that linked the lower floor classrooms and upper floor hall. Results showed that the thermal chimney system operates well in hot and humid tropics, including on cooler days. However, [6] shows that an attempt at a passive stack retrofit, incorporating the principle of airflow due to buoyancy, did not sufficiently enhance air velocity in a Housing and Development Board (HDB) residential apartment building in Singapore. However, a modified active stack was shown to be effective, operating an airflow boost when needed based on the suction effect induced by a fan fixed at the top of the

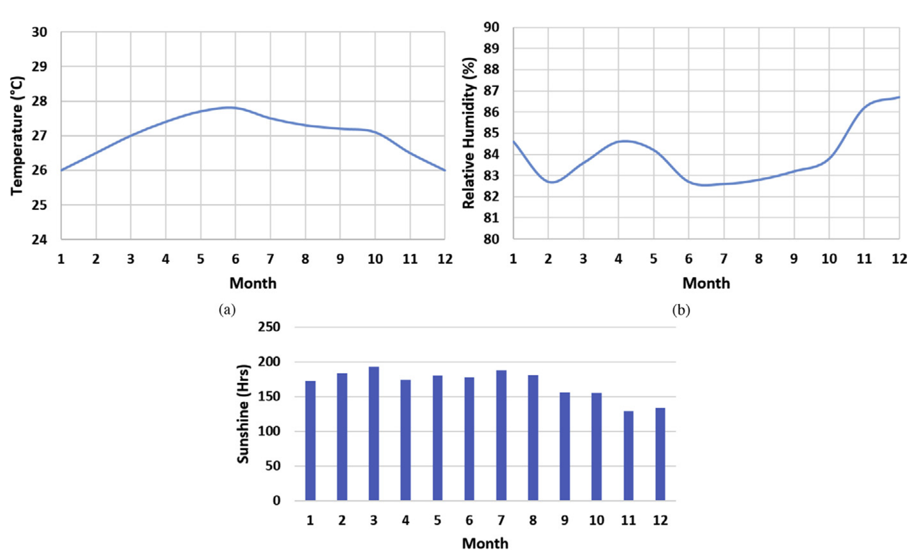

Fig. 1. Average monthly (a) temperature, (b) humidity, and (c) sunshine hours in Singapore [3].

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