Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Investigating the New Product CCF-DGU Without Coatings for Thermal Comfort in a Tropical Indoor Environment

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ARTICLE INFO

Article history:
Received 7 February 2023
Received in revised form 5 May 2023
Accepted 18 May 2023
Available online 30 May 2023

Keywords:
Closed cavity; adaptive; façade; energy efficiency; thermal comfort; hot-humid climate

ABSTRACT

A closed cavity facade (CCF) is an airtight, unventilated construction with an automated shading system, double glazing on the inside, and single glass on the outside. The above method effectively manages solar energy and natural light into the construction. Multiple CCF-DGU designs were tested using Window 7.8, EnergyPlus, and DesignBuilder. Then, the designs were compared to grey-coated single-glazed units (SGUs). A unit case study on Penang Island, Malaysia, prompted the examination. Compared to SGUs, the CCF-DGU provides improved thermal performance and comfort. In Malaysia's humid tropical climate, CCF-DGU designs reduce operating temperature percentages better than SGUs. The annual reduction rate is 81.22% to 96.85%, providing thermal comfort. The study highlights the benefits of implementing a novel CCF technology tailored to Malaysia's climate. The findings suggest that enhanced glazing technologies could improve building operational temperatures and occupant comfort.

1. Introduction

According to Tuck *et al.,* [1], the hot and humid climate in Malaysia leads to the attainment of maximum interior temperatures in buildings ranging from 31 - 35°C. Abdo and Al-Absi [2] have posited that the condition of thermal comfort is achieved when the ambient temperature falls between 30 and 32°C. The thermal comfort temperatures for climatic conditions in Malaysia have been seen to fall within a comparable range, as indicated by both international and local regulations and guidelines for buildings that rely on natural conditioning. In Malaysia, the consumption of electrical energy in buildings is notably amplified by the use of air conditioning systems. This is primarily attributed to the prevailing habit of people spending a considerable duration of their time inside [3]. There has been a significant increase in the use of energy since 1997. The National Energy Balance report of 2018 [4] revealed that around 49.5% of the overall power usage may be attributable to the corporate and residential sectors [2].

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https://doi.org/10.37934/ard.104.1.114

Cuce [5] and Shaeri *et al.,* [6] have shown that the use of glass in buildings leads to the dissipation of around 50 % of the building's energy. The use of energy is mostly impacted by the existence of window glass. The careful choice of glass apertures has a crucial role in maximising both thermal comfort and energy efficiency. The International Energy Agency and the Global Alliance for Buildings and Construction [7] have asserted that the external envelope of a building fulfils the function of providing insulation and controlling the immediate surroundings of the structure. Gelesz and Reith [8] assert that the progress made in window and glazing technology, together with the emergence of novel coatings, has led to a significant improvement in the energy efficiency of windows. Conventional glazing techniques exhibit suboptimal heat utilisation and promote bidirectional heat transfer throughout both the winter and summer seasons. Over the last two decades, there has been significant growth in the domain of sustainable building design. The scope of this growth goes beyond the mere advancement of high-performance façade systems, which provide enhanced thermal insulation and flexibility in response to external factors and occupant needs. The primary objective of these advances is to reduce energy use and improve thermal comfort. The internal temperature is influenced by several elements, such as the orientation of the building in relation to shadow and the thermal properties of the construction materials [9,10].

Several scholarly investigations have explored the potential of using CCF as a strategy to reduce building energy consumption and improve indoor air quality [11,12]. Scientific testing has been conducted on the CCF facade in diverse metropolitan settings, resulting in promising findings. These findings demonstrate a range of reductions in total energy consumption, spanning from 21.8 - 40.7 %. Similarly, there are observed decreases in energy demand within the same range. Furthermore, the measurement of the cooling load yielded a value of 79.8 KWH/M^2. Moreover, a significant enhancement in operational temperature was recorded, reaching 100 % for operating temperatures beyond 27°C [11].

2. Methodology

The research included many distinct phases. Prior to establishing the ideal temperature range for the CCF transition, field measurements were conducted to assess the interior environment in a diverse range of naturally ventilated residential spaces. In addition, the numerical research investigated the effects of CCF on reducing operating temperatures by varying transition temperatures and quantities.

2.1 Field Measurement

The indoor air temperature (T_i) was recorded at four specific positions inside a building, including 85% glass facades, each facing a different direction, as seen in Figure 1. The case study is situated on Penang Island, Malaysia. The data collection period was from March 3rd - 8th, 2023, using an Ohm Srl data logger type DO9847. Subsequently, the measurements are consistently recorded at a vertical distance of 1.1 m from the ground level within the room, as specified by the Ashrae Standard [13]. These measurements are conducted in areas that lack any form of mechanical ventilation or an operational fan, ensuring that a fair comparison can be made with a product that possesses a closed cavity and lacks any ventilation openings.

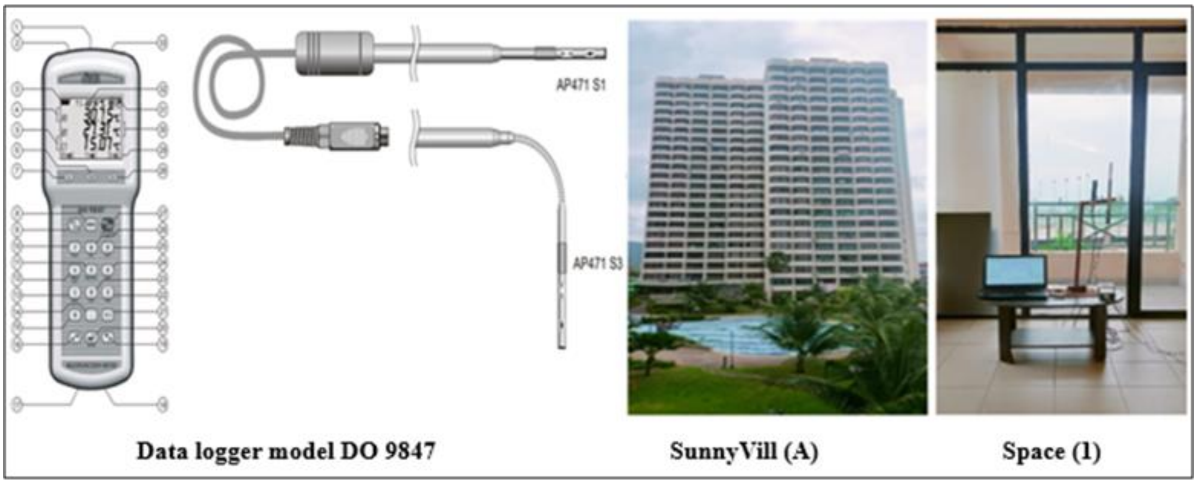

Fig. 1. The instrument used in the field measurements, the selected building for the field measurements, and examples of the instrument installation

Table 1
A summary of the measured T_i in all case studies

Building	Room	Level	Orientation	Indoor air temperature			
				Max.	Min.	Aver	Fluctuation
A	Space1	03	East	35.75	29.7	32.7	6
	Space2	020	North	34.65	29.8	32.2	4
	Space3	020	West	35.8	29.8	32.8	5
	Space4	020	South	35.8	29.3	32.5	5
	Average			35.5	29.6	32.55	5

2.2 Simulation Investigation

This study aimed to address the primary research topic of how to improve the thermal and comfort performance of buildings utilising CCF-DGU without the need for coatings. To do this, several CCF configurations were examined and compared to a baseline model, which consisted of a typical SGU with grey covering. In order to achieve this objective, the CCF was constructed using several modelling programmes, including WINDOW 7.8, Energy Plus 8.9.0 and DesignBuilder 6.1. Subsequently, the interior climate and energy performance of the CCF were simulated for the specific climatic conditions of Malaysia.

The simulation research was conducted using EnergyPlus (v8.9) and DesignBuilder (v6.1) in collaboration. EnergyPlus is widely recognised as a highly regarded software package for simulating energy and thermal performance in buildings [14,15]. Numerous scientists have used it as a means to forecast the thermal characteristics and efficacy of buildings outfitted with CCF technology. DesignBuilder is a software tool that provides a comprehensive graphical user interface for the energy modelling programme EnergyPlus [16,17].

2.2.1 Build-up of CCF-DGU

We have compiled a variety of test configurations to determine how well CCFs operate in Malaysia's typical climate. Different uncoated glass panes and two varieties of integrated Venetian blinds were considered as possible shading solutions. The innermost pane of the DGU is tempered to a thickness of 6 mm for safety purposes, while the outer epidermis glass and DGU glass are both 4 mm thick. Figure 2 provides schematic representations of the various CCF configurations (CCFD1, CCFD1-VB1 and CCFD1-VB2) [12].

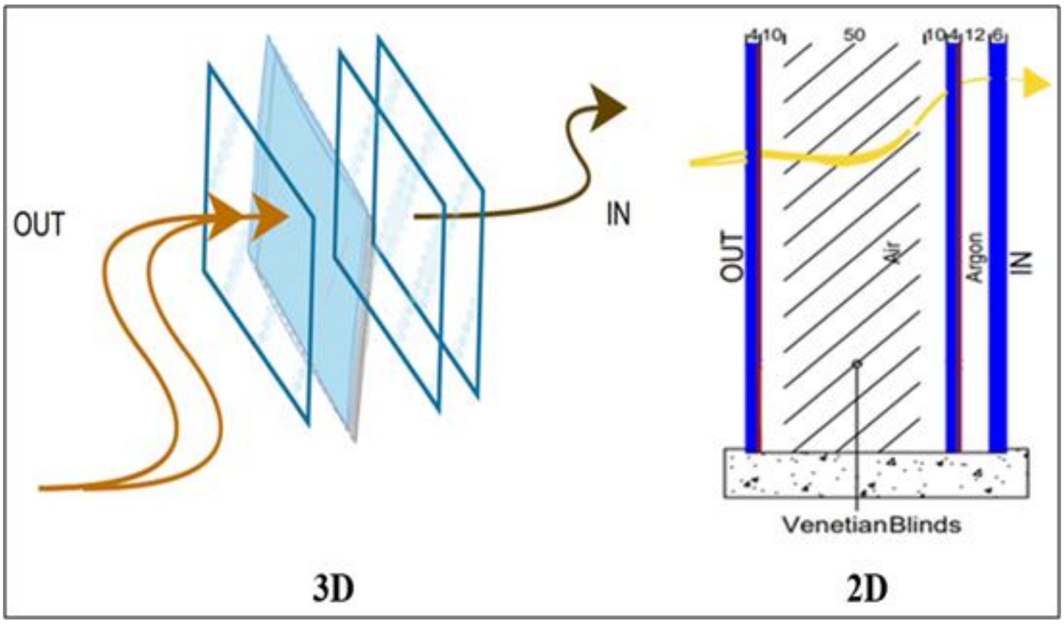

Fig. 2. Schematic diagrams of the CCF-DGU simulated

The three groups, namely CCFD1, CCFD1-VB1 and CCFD1-VB2, exhibit three distinct layouts, each characterised by the presence or absence of blinds. The first layout, VB0, does not include any blinds. The second layout, VB1, has white blinds positioned at a 45° angle. The third configuration, VB2, showcases wooden-coloured blinds also set at a 45° angle. Whereas venetian blinds are often preferred as an integrated shade device inside the cavity because of their adjustable rotation angle, which provides users with more control.

The performance parameters of the constructed CCF setups were determined using the Window 7.7 software, and the results of these computations are shown in Table 2. The aforementioned properties include the thermal transmittance U-value, the solar heat gain coefficient SHGC-value, the solar transmittance T_{sol}, and the visual solar transmittance T_{vis}. The algorithms used in this software were created by the Lawrence Berkeley National Laboratory (LBNL) and are based upon the internationally recognised standards for evaluating the thermal and solar-optical characteristics of glazing systems, namely ISO 15,099 and ISO/EN 10,077.

The parameters of Table 2 were inputted into EnergyPlus and DesignBuilder software in order to assess the performance of the CCF configurations compared to a baseline SGU with a grey covering. In instances where the radiation level incident on the façade falls below 250 W/m2, the integrated Venetian blinds are fully withdrawn. Conversely, when the radiation level is above this threshold, the blinds are automatically activated and deployed.

Table 2
Performance values of CCF-DGU glazing configurations simulated [11]

Groups	Glazing configuration	U-value (w/m2k)	SHGC	T_{sol}	T_{vis}
Baseline	SGU with gray coating	5.882	0.670	0.550	0.559
	CCFD1	1.672	0.653	0.531	0.701
Group	CCFD1- VB1	1.240	0.259	0.123	0.169
	CCFD1-VB2	1.247	0.286	0.039	0.045

2.2.2 Location and climate class

The process of validating CCF technology was conducted in Penang, Malaysia. The meteorological data file used in this implementation is derived from a 15-year span of historical weather data (2003–2017). The compilation of this data was conducted using the TMY/ISO 15927-4 methods as outlined by [18]. The data was obtained via the Climate One Building website [19]. The weather data file provides information on the monthly averages of outdoor air temperature (T_o), relative humidity (RH), and global solar radiation, as shown in Table 3.

Table 3
Climatic data for the selected location [2]

Location	Climate class	Max. monthly outdoor temperature	Min. monthly outdoor temperature	Max. RH %	Min. RH %	Max. monthly global radiation	Max. monthly global radiation
Penang-Malaysia	Tropical-humid	33°C	26°C	97 %	55 %	9.1	7.1

2.2.3 Building model (case study)

The residence unit consists of three bedrooms, two bathrooms, a kitchen, and a living room. Spaces 1, 2, 3 and 4 were chosen for development as a simulation model due to their distinct characteristics, namely glass facades and a high thermal environment, which align with the four main directions. The research encompasses all facets of the structure. Space 1 is located on the third level of the building and may be classified as a medium-sized bedroom, with around 24 m^2 of floor space. Space 2 is situated on the northern side of the building and serves as a living room, with a floor surface of 26 m^2. Space 3 is situated on the western face of the building and serves as a middle bedroom, including a floor space of about 22 m^2. Furthermore, space 4 is located on the southern side of the building. The dimensions of the living area are 26 m^2, located on the 20th floor. The measured ceiling height in the specified locations is 2.85 m. Furthermore, a significant proportion of the outside walls, precisely 85 %, are made of glass panels that are oriented in the four fundamental directions of east, north, west, and south. The construction of a comprehensive apartment model with precise measurements, materials, and openings is evident from the depiction in Figure 3 and the data shown in Table 4.

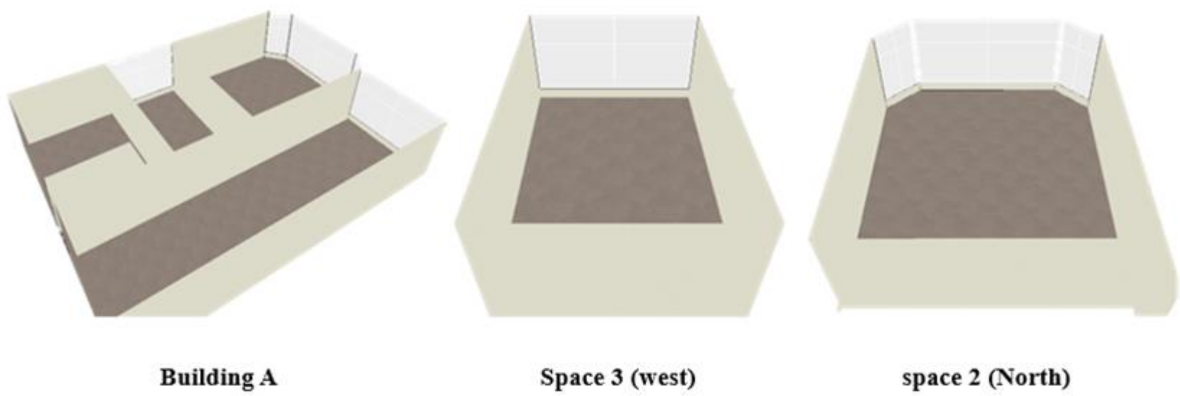

Fig. 3. The original building and room and the developed numerical model

Table 4
Materials used for the numerical model and their thermal properties [2]

Item	Description	Conductivity (w/m-k)	Total thickness (mm)	U-value (w/m2-k)
	External cement render	1.00		
External walls	concrete wall	1.13	130	3.398
	Internal cement plaster	0.72		
	Cement plaster	0.72		
Internal partitions	Brick wall	0.72	126	2.299
	Cement plaster	0.72		
Floor	Tiles	1.30	110	2.86
	Concrete slab	1.40		
Glazing	Single Gray glass 6mm +Aluminum frame		6	6.121

The findings of a comparison between the expected T_i by EnergyPlus utilising updated meteorological data and the observed T_i in the field from March 3rd - 8th, 2023, are shown in Figure 4 [2,20]. The purpose of this comparison was to assess the validity of the newly created building model. The findings indicate that the observed T_i and the estimated T_i exhibit a mean agreement within a margin of error of just 1 %. The predictive accuracy of T_i, as revealed by Marczyk *et al.,* [21], was further validated by a correlation value of around 0.95.

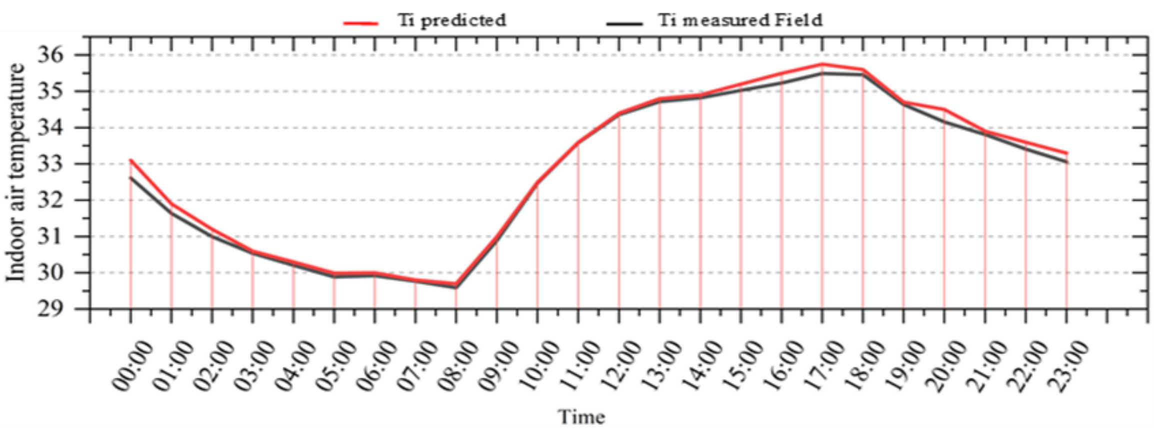

Fig. 4. A comparison between the measured and predicted T_i

2.2.4 Modelling and performance simulation of the CCF-DGU

Energy Plus 8.9.0 and DesignBuilder (v8.9) are well recognised as very sophisticated software applications for doing building performance assessments. The aforementioned study employed a model to simulate the indoor climate and energy demands of the building. This model considered various factors, such as the performance of the building's façade, the characteristics and activation settings of the integrated blinds, and the configuration of the heating, ventilation and air conditioning (HVAC) system. These factors were taken into account in order to accurately assess the indoor climate and energy requirements of the building [22]. In light of this, an assessment was conducted on four models for each of the four orientations of the facades, as shown in Table 1. Each model in the study depicts a solitary chamber with a single facade that is 85 % glazed. Throughout the duration of the experiment, three individuals inhabit these models continuously for a whole day, seven days a week.

To ensure the precision of the outcomes aligned with the new CCF-DGU façade concept and to provide reliable comparisons between pre- and post-installation of the CCF façade, all experiments were carried out in a controlled setting without any mechanical ventilation. Furthermore, all glass contacts, regardless of whether they were in the measured field or simulation, were closed.

Table 2 and Figure 2 show that the CCF-DGU simulations were done with the Energy Plus software and the SHGC, Tvis and U-value variables. This will aid in determining the optimal categorization for attaining the previously specified attributes of venetian blindness. This research used operational temperature, including indoor air temperature and radiant temperature, as a means to assess thermal comfort on a monthly and yearly basis across all models. Subsequently, the experiment was conducted on a monthly basis, with March selected for the eastern and western regions, June for the northern region and January for the southern region. These months were chosen because of their consistently elevated radiant temperature ratios throughout the course of the year.

3. Results and Discussion

3.1 CCF1-DGU Without Configuration, Monthly-Round Performance

Figure 5 compares the peak daily operating temperature of the CCFD without coatings to the reference condition, which is when there is no CCFD present. According to the findings, the CCFD application demonstrated statistically significant reductions in the daily peak operating temperature in comparison to the reference condition. On the northern facade, the average monthly operating temperature peak ranged between 33.66 and 28.67°C, which is lower than the reference case's 35.08°C. The average monthly operating temperature peak on the southern facade ranged between 33.31 and 29.75°C, which is lower than the 36.23°C in the reference case. It ranged from 34.15 - 31.25°C versus 35.91°C for the reference case at the eastern facade and from 34.25 - 30.86°C versus 36.11°C for the reference case at the western facade.

Simulation demonstrated that CCFD1-VB1 with incorporated horizontal white venetian shutters is the most efficient CCFD. For each of the four orientations in Malaysia's humid tropical climate.

In addition, Figure 6 displays the percentage of quantitative efficiency (SGU / (SGU - CCF) * 100) relative to SGU at each facade. The optimal enhancement for each group was determined by contrasting the results obtained at their respective environmental operating temperatures. The northern facade has a CCFD1 value between 17 – 79 % and 31 – 70 %, while the southern facade has a value between 31 – 70 % and 19 – 52 %, and the eastern facade has a value between 19 – 52 % and 20 – 57 %.

As shown in Table 2, the preponderance of the improvements with CCFD-VB1 are attributable to the value of the SHGC when venetian blinds are incorporated into the CCFD cavity. With a SHGC of 0.259 for CCFD1-VB1 with white venetian blinds, CCFD is more effective than SGU at minimizing solar gain through the facade, which contributes to energy consumption in a climate where mechanical cooling predominates because of its humid tropical climate, where mechanical cooling is characteristic. The decrease in cooling load is predominantly responsible for the benefits generated by CCFD [11].

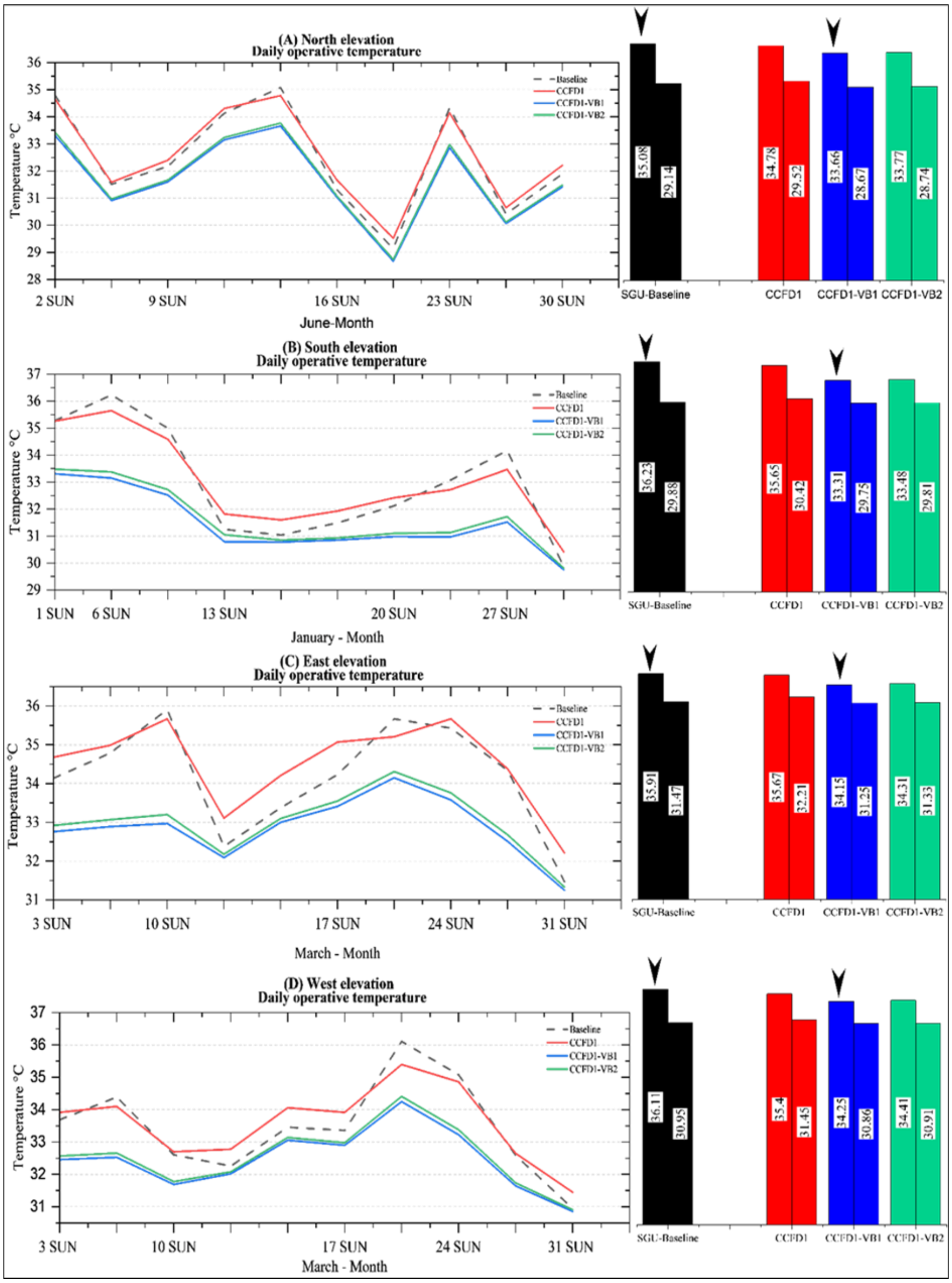

Fig. 5. Shows the average daily and monthly highs and lows for each CCFD1 without coatings is north (A), south (B), east (C) and west (D) façade, respectively

Compared to the blinds in CCFD1-VB2, the blinds in CCFD1-VB1 exhibit a 1 % performance improvement. As shown in Figure 5 and 6, the southern, western, eastern and then northern facades are optimal for enhancing operational temperature. As the evaluation of facades is based on four directives and the month with the maximum radiative temperature ratio, this is due to the orientation and thermal radiation ratio.

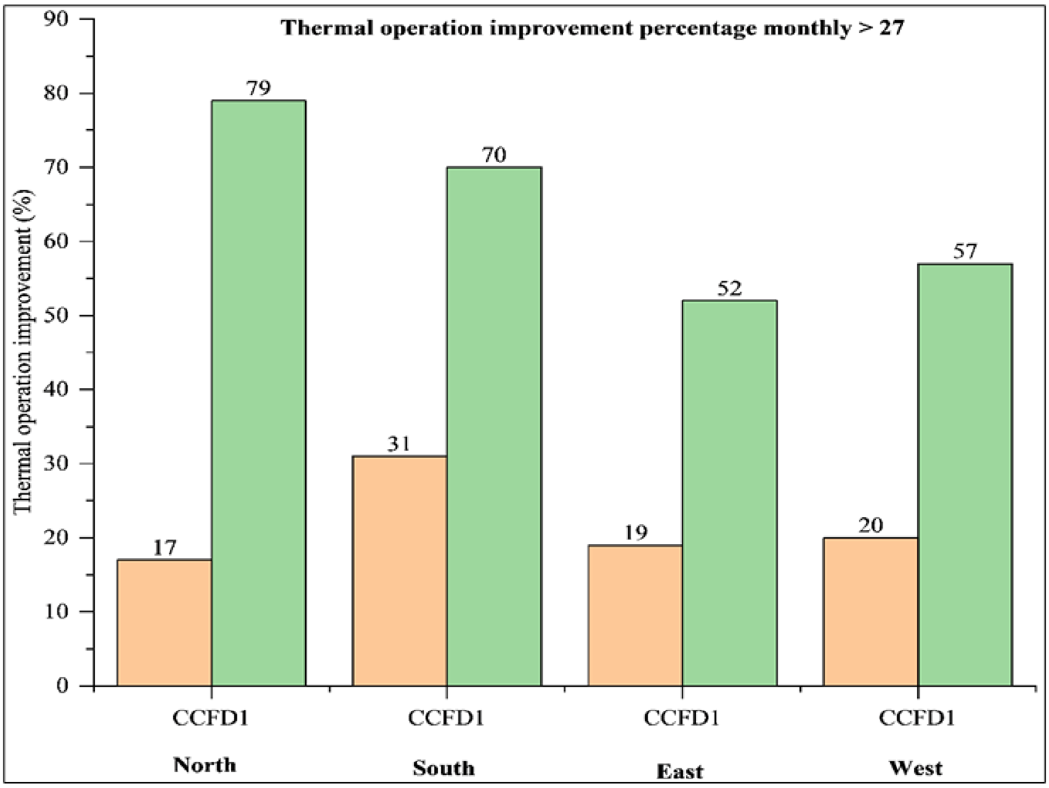

Fig. 6. Monthly-round daily means of the percentage of operating temperature enhancement for CCFD1 for the north, south, east and west facades

3.2 CCF1-DGU Without Configuration Year-round Performance

Throughout the year, the performance and effectiveness of CCFD were compared to baseline (SGU) (i.e., for operational temperature comparison). Figure 7 depicts a year-round decline in the optimum operating temperature for each of the evaluated facades; for instance, the northern facade demonstrates a drop in maximum temperature of 1.21°C, from approximately 35.4 - 34.19 °C, and a decrease in minimum temperature of 0.07°C, from 28.98 - 28.91°C. This corresponds to an improvement rate of 14 – 57 %, as depicted in Figure 4.13 for the CCFD1 group. The southern facade's uppermost limits decreased by 0.74°C, from 34.17 - 33.43°C, and the lowermost limits decreased by 0.03°C, from 29.39 - 29.36°C. This represents a 10 – 66 % improvement rate for CCFD1. The eastern facade exhibited a decrease in maximum temperature of 2.14°C, approximately from 36.62 - 34.48°C, and a decrease in minimum temperature of 0.08°C, between 29.42 and 29.34°C, with an improvement rate of 22 – 75 % for group CCFD1. In addition, the western façade shows a decrease of 2.81°C in the highest limits, from 37.03 - 34.22°C, and a decrease of 0.1°C in the lower limits, from 29.22 - 29.12°C, with a 28 – 78 % improvement for CCFD1.

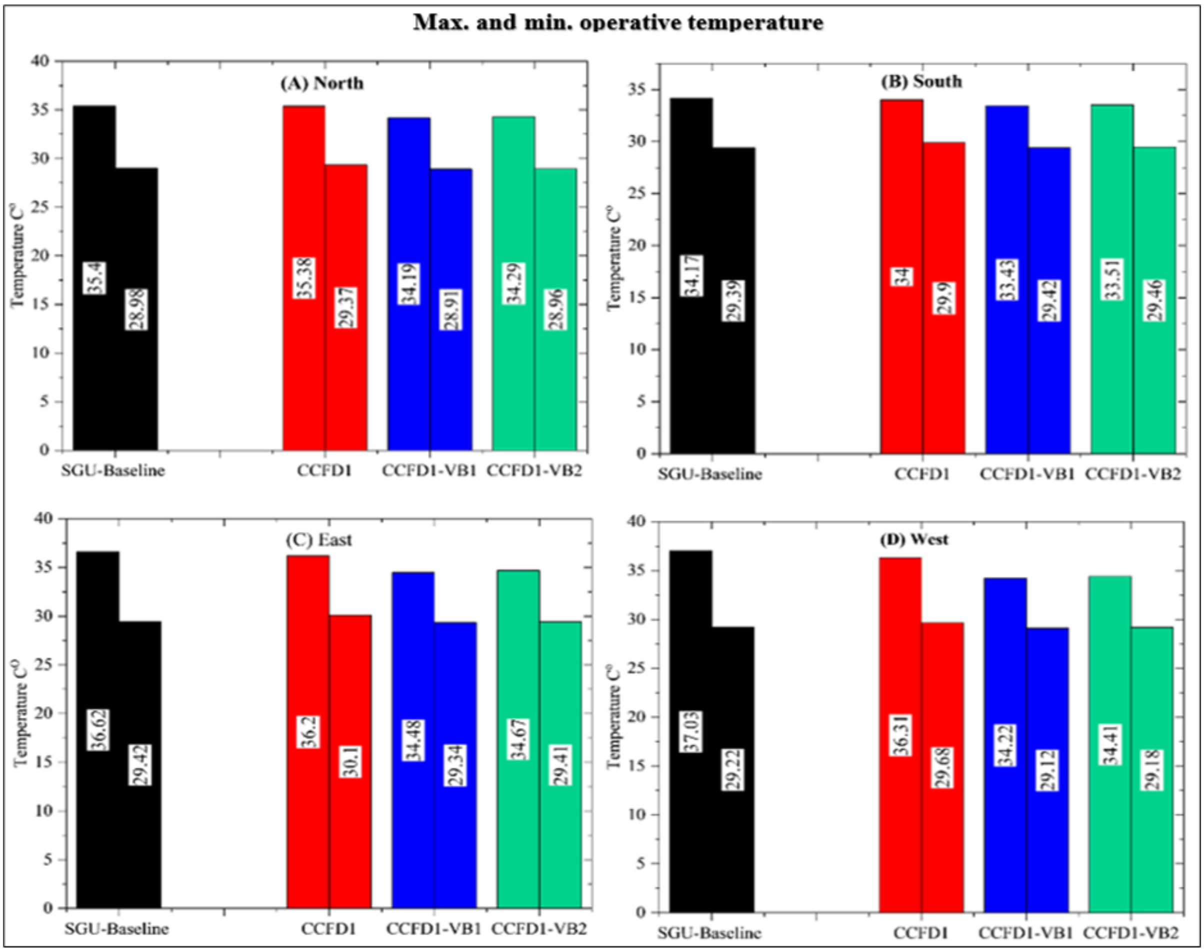

Fig. 7. Shows the average annually highs and lows for each CCFD1's north (A), south (B), east (C) and west (D) facades, respectively

We observe that the maximum temperatures, which are over 27°C, decrease by 1 - 3 °C in the utmost limits, i.e., between 34 and 33°C, whereas the minimum temperatures, which are between 30 and 28°C, decrease by 0.01 - 0.1°C. As a consequence, the operating temperatures (internal temperature plus radiant temperature) were achieved with a modest increase in thermal comfort factors compared to a facade without coating. Due to the humid tropical climate, this reduces the cooling load in a climate where mechanical cooling is the norm, which in turn lowers energy consumption by up to 28 - 30 % [11]. The western facade has improved the most, as shown in Figure 7 and 8, then the eastern facade, the northern facade and the southern facade. This is because of the orientation and thermal radiation ratio.

As Table 2 shows, most of the benefits of CCFD-VB1 are due to the value of the SHGC when venetian blinds are added to the CCF cavity. A SHGC of 0.259 for CCFD1 built with white venetian blinds Compared to the blinds in CCFD1-VB2, the performance of the lighter-coloured blinds in CCFD1-VB1 increases by 1 %.

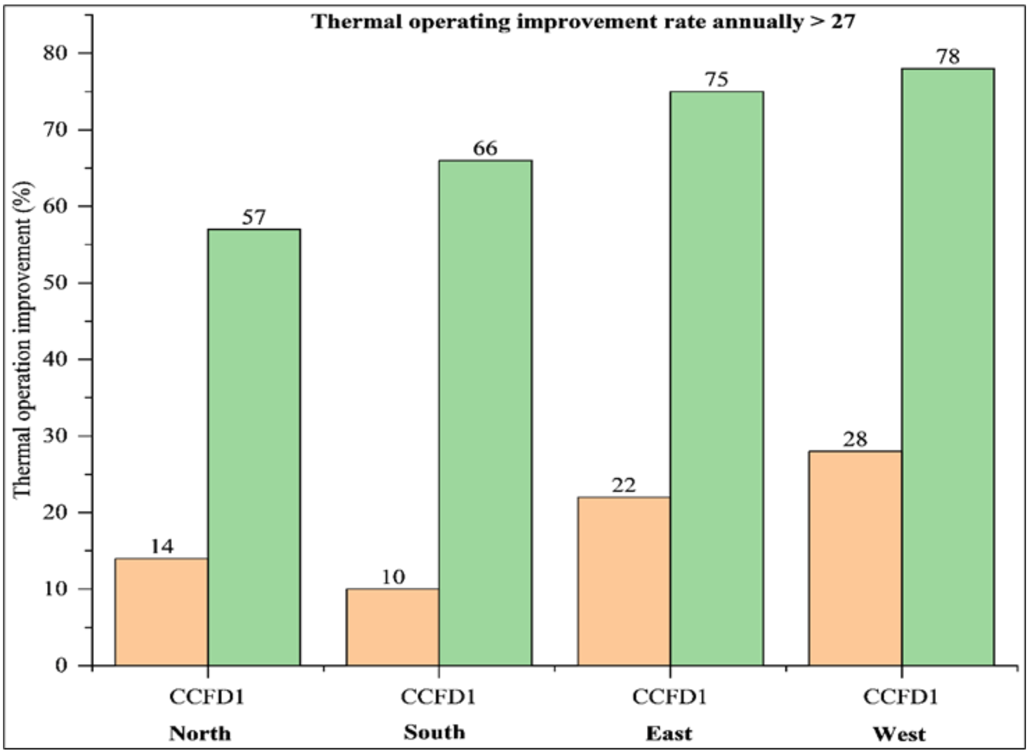

Fig. 8. Annually, round daily means of the percentage of operating temperature enhancement for CCFD1 for the north, south, east and west facades

Table 5 presents a comparative analysis of the current study with previous research conducted by Michael and Overend [11,12]. The study was conducted in Malaysia, which has a humid tropical climate. The research examined all facade orientations individually and adopted a progressive approach, starting with the peak months and gradually moving towards the annual average. The monthly improvement rates for operating temperatures on the northern facade ranged from 17 – 79 %, while the southern facade experienced rates between 31 % and 70 %. The eastern and western facades saw improvement rates ranging from 19% - 52 %, and the western facade specifically had rates varying from 20 - 57 %. Furthermore, it is observed that the average operating temperature exhibits an annual improvement ranging from 81.22 - 96.85 %.

Previous research was conducted annually in nine distinct geographical locations, namely Rio de Janeiro, Dubai, Sydney and New York. The research took place within an enclosed space that had three sides open, specifically facing the south, east and west directions. The temperature comfort range falls within the range of 68.2 - 89.6 %. Table 5 also demonstrates that the improvement percentages observed in the studies carry a notable resemblance to the annual outcomes. Nevertheless, it is worth noting that this particular investigation revealed a significantly greater improvement in the context of a humid tropical climate.

Table 5
Comparison of previous investigations with the current CCF study

The study	Location	Climate Characteristic	Elevations	Thermal operation improvement percentage monthly > 27	Thermal operating improvement rate annually > 27	Configuration CCFD
The current study	Penang - Malaysia	Tropical – humidity	North South East West	17 – 79 % 31 – 70 % 19 – 52 % 20 - 57 %	81.22 – 96.85 %	CCFD without coatings
Previous study [11,12]	Rio de Janeiro Dubai Sydney New York	Tropical savanna Dry desert hot Temperature humidity Temperature humidity	A room with three opens sides, south, east and west.	N/A	68.2 – 89.6 %	CCFD with coatings

4. Conclusions and Future Work

Thermal comfort (operating temperature) is impacted by the new CCF. A tropical-humidity climate was used to test SGU and CCF combinations using Design Builder, EnergyPlus and Windows 7.8. According to the performance analysis, SGUs with grey coatings are less thermally comfortable than CCF. Final thoughts are:

i. The study effectively demonstrated a reduction in the operational temperature peaks through the utilization of CCF without coatings.
ii. The utilization of CCFD1-VB1 resulted in achieving the maximum reduction in the peak operating temperature.
iii. Throughout the entirety of the year, the CCFD exhibited commendable performance in ensuring occupiers comfort. Notably, it achieved a maximum annual reduction of 2°C in peak operating temperature while also maintaining a minimum annual decrease of 1°C.

Compared to the baseline SGU, it was seen that each CCF system option without coatings had a significant increase in peak operating temperature, ranging from 81.2 - 96.85 %. This meant that thermal comfort was effectively achieved. This improvement was observed in tropical climates characterised by high relative humidity. The installation of Venetian blinds within the cavity resulted in enhanced thermal transmittance and SHGC. In regions where cooling is the primary concern, the consumption of energy tends to rise due to the implementation of cooling control factors (CCF), which effectively mitigate solar heat gain through the building's exterior. Furthermore, this study has generated novel avenues for future research, including the validation of simulated CCF, the exploration of overheating in the CCF cavity, and the analysis of CCF's performance under different blind control strategies and slat angles.

Acknowledgement
This work was produced as part of a research project for a master's degree. The authors are very grateful to School Housing, Building and Planning, University Sains Malaysia (USM), for providing this opportunity.

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