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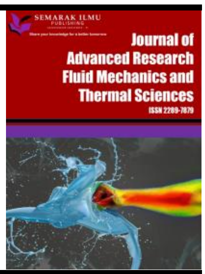

Investigation of CCF with TGU as Inner Skin to Reduce Peak Operating Temperature for Thermal Comfort in an Indoor Environment in a Hot, Humid Climate

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ABSTRACT

A closed cavity facade (CCF) is “a sealed, non-ventilated cavity with an automated shading device that, at its simplest, consists of double or triple glazing on the inside and single glazing on the outside”. The dynamic properties of this technology enable the fluid control of solar energy and daylight entering the structure. Several CCF designs were investigated in EnergyPlus and DesignBuilder, and the outcomes were compared to the present state (a single-glazing unit (SGU) with grey coating). The investigation was founded on a case study of a Penang Island, Malaysia, condominium. Comparing CCFs with traditional SGU systems reveals significant thermal performance and occupant comfort enhancements. CCF configurations performed well throughout the year, with maximum operational temperature reductions 40–91% better than traditional SGUs in Malaysia's humid tropical climate. Further investigation revealed that the glass coating and sun shading capabilities substantially contribute to reducing the interior temperature and enhancing the comfort of the building's occupants. The greatest performance was achieved by combining a nanocoating (83/58) and an E-low coating (83/23) (T_{vis}/T_{sol}) with a Venetian blind. In light of this, it is essential to carefully consider which coatings to use when installing CCF in such conditions. In all of these regards, the study concentrates on the fact that developing and implementing suitable combinations of a new closed-cavity facade for Malaysia's climate can result in substantial gains. The results demonstrate that building operational temperatures and comfort can be enhanced, highlighting the need for innovative glazing technology.

1. Introduction

The combination of Malaysia's tropical climate (i.e., hot and humid) and the effects of global warming has led to an increase in the percentage of cases where people have complained about the inside temperature being too high for their comfort. Consequently, people typically utilise air conditioning to bring down the temperature and regain their comfort [1]. Most people spend 87%–

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100% of their time indoors [2]. Therefore, air cooling accounts for more than half of all building energy use [3,4].

Several on-the-ground investigations conducted in Malaysia's hot and humid environment have found that average indoor temperatures range from 31 to 35°C [5]. The average temperature found to be comfortable in the thermal comfort investigations is 28°C, with temperatures in the range of 30°C to 32°C being considered suitable [6]. Additionally, the models estimating the thermal comfort temperatures for the Malaysian climate can be found in global and local standards and guidelines for naturally conditioned buildings, such as BS EN 15251, 2007; BSEEP, 2013; ANSI/ASHRAE Standard 55, 2017; MS 2680, 2017 [6,7]. Most of a person's life is spent inside, one of the largest consumers of power in Malaysia is the air conditioning industry [8]. For instance, between 1997 and 2018, there was a 200% rise in power use. The National Energy Balance reports that in 2018, the commercial and residential industries accounted for 49.5% of total power usage [6].

About half of a building's total energy loss can be attributed to glass [9,10]. Whereas the glass in a building's windows has the greatest impact on energy use. So careful planning and selection of the glazed apertures is required to achieve optimal thermal and visual comfort with minimal operating energy consumption. While the "skin" of a building serves a similar function to that of human skin by acting as a barrier and regulating the temperature inside the building and the comfort of its occupants [11]. However, recent advancements in window and glazing technology, as well as the use of a variety of coatings, have led to dramatic improvements in the thermal performance of windows [12]. On the other hand, traditional glazing methods have poor performance characteristics that cause considerable heat loss in the winter and unwanted heat gain in the summer. Consequently, sustainable building design has undergone a dramatic shift over the past two decades, shifting towards a more holistic design approach to create high-performance facade systems that can provide high thermal insulation and react to the outdoor environment and the needs of occupants to reduce energy demands and increase thermal comfort [13]. By focusing indoor temperature, building design characteristics (such as orientation, shade), and thermal qualities of materials [13,14].

Several studies have explored how improving the indoor atmosphere using CCF could reduce energy consumption in buildings [15]. The closed cavity facade has been tested by scientists in a variety of cities (Dubai, Sydney, New York, Shanghai, London, Toronto, and Helsinki) with impressive results: reductions in total energy consumption (17.9–36.9%), energy demand (17.6-36.9%), cooling load (83.6 kWh/m^2), and operative temperature (100% for operative temperatures > 27 °C) [16].

The CCF is an innovative form of the DSF. There is a cavity with an integrated shading device between the exterior single glass and the inside double or triple glass [16]. The technical and operational advantages of CCFs over DSFs include, but aren't restricted to, preventing dust and particle accumulation and settlement in the cavity, reducing maintenance costs, improving airflow control, extending the service life of components housed within the cavity, etc [17,18]. As an alternative to double-skin ventilation, CCF panels can be sealed and supplied with pressurised, filtered, and humidified air [16]. This helps to maintain a consistent pressure within the sealed cavity, prevent humidity from developing, and keep the cavity from overheating. The thickness of a CCF is just 130–150 mm in theory, but in reality, it is more like 200–250 mm [17]. A typical DSF, whether it is vented from the outside or the inside, has a maintenance space of around 600 mm between the glass skins. The CCF's key advantage is that it allows façade prefabrication, which reduces manufacturing and installation costs and increases efficiency in the use of the building's usable area [16].

There are only a few instances of scientific works that provide a comprehensive analysis of CCF's essential features, performance, advantages, and limitations because it is such an innovative advancement in the field of glazed façade technology. In particular, there is a dearth of research that thoroughly examines the performance of different CCF designs across a wide range of environmental circumstances. Therefore, the objective of this research is to investigate the thermal performance of glazed facade constructions using CCF with triple glazed units (TGU) as glazed inner layers to reduce external heat gain and interior temperature. When compared to the standard SGU with a grey coating, this façade technology is more flexible for the tropical climate in Malaysia. The use of CCF in the design of double-skin façades in the twenty-first century is a significant technological advancement [15]. It's an exciting area of study because of the country's hot and humid environment. The advantages of utilising a CCF for buildings in Malaysia's tropical environment, as well as the qualities necessary for an efficient CCF, are not yet fully established, and additional research is required.

2. Methodology

There were a few stages involved to this investigation. Before determining the optimal temperature range for the CCFs transition, field measurements of the indoor climate were taken in a variety of naturally ventilated homes. The impact of CCFs on lowering operative temperatures and decreasing humidity was then examined using a numerical study with a range of transition temperatures and amounts.

2.1 Field Measurement

As shown in Figure 1, indoor air temperature (T_i) was measured at four distinct locations with 85% glazed facades in four orientations. The case study takes place on the Penang Island Malaysia. The measurements were collected in 3rd until 8th March 2023 with an Ohm Srl data logger model DO9847. Then, the measurements are taken continuously at a height of 1.1 m above ground, with the ground closer to the centre of the floor area, the room according to ASHRAE [19], and in spaces completely devoid of mechanical ventilation or a fan completely closed, as it will be hard to compare with a product that does not contain any ventilation openings characterised by a closed cavity.

Data logger model DO 9847 | SunnyVill (A) | Space (1) | Space (2)

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

All facades were measured for a full 24 hours in each space, and the resulting T_i values for each case study are shown in Table 1. The highest T_i was recorded at 35.8°C, with an average of 35.5 °C across all locations; the lowest T_i was recorded at 29.3°C, with an average of 29.6°C. Furthermore, in most areas, the average daily variation of T_i was up to 5°, which can be attributed to a wide variety of causes, including weather conditions during the measurements, specific locations, and the impact of solar radiation on the surface of higher-floor areas.

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

In order to address the primary question driving this study—"how to improve the thermal and comfort performance of buildings using CCFs"—multiple CCF designs, geometries, and materials were studied and compared to the baseline, a traditional SGU with a grey coating. This was achieved by employing a number of different modelling tools (WINDOW 7.8, Energy Plus 8.9.0, and DesignBuilder 6.1) to simulate the CCFs' indoor environment and energy performance in the Malaysian climate.

EnergyPlus (v8.9) and DesignBuilder (v6.1) were used in cooperation with each other to conduct the simulation study. EnergyPlus is one of the most reputable energy and thermal performance building simulation software packages [20,21]. It was used by several researchers as a reliable tool for predicting the thermal behaviour and performance of structures using CCFs. Additionally, DesignBuilder is a graphical user interface for the energy modelling software EnergyPlus, and it is simulation software [22,23].

2.2.1 Build-up of CCF configuration

We have assembled a variety of setups to test out to see how well CCFs operate in the weather conditions typical of Malaysia. Different coated and uncoated glass panes, as well as two types of built-in Venetian blinds, were all taken into account as potential shading solutions. For reasons of safety, the innermost pane of the TGU is tempered to a thickness of 6 mm, while the outside skin glass and TGU glass are both 4 mm thick. Schematic representations of the different CCF setups (CCF1, CCF2, CCF3, CCF4, and CCF5), are provided in Figure 2 [15].

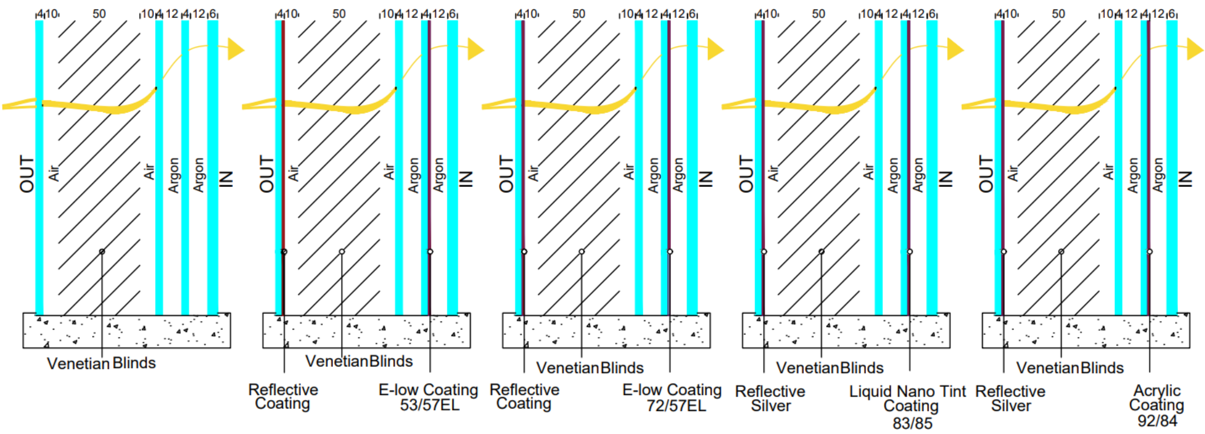


Fig. 2. Diagrammatic renderings of the five groups of CCFs configurations

Groups CCFT1, CCFT2, and CCFT3 each have three possible layouts: one with no blinds at all (VB0), one with white blinds at 45° (VB1), and one with wooden-coloured blinds at the same angle (VB2). In contrast, groups CCFT4 and CCFT5 each have three possible layouts: one with reflective silver 20/16 and white horizontal blinds at 45° (VB1), one with reflective silver 38/30 and white blinds at 45° (VB1), and the last one integrates reflective silver 56/47 and white horizontal blinds at a 45° slat angle (VB1).

Venetian blinds are preferred as a shade device integrated into the cavity because their rotation angle can be adjusted, giving the user more control. Systems in the first group (CCFT1) have uncoated glass panes, while systems in the second group (CCFT2) have a high-performance coating 53/23 LE (T_{vis}/T_{sol}) applied to surface No. 6 and a reflective coating reducing solar radiation entering the CCF cavity applied to surface No. 2 (numbering surfaces from the outermost to the innermost). The fourth group (CCFT4), however, has a high-performance liquid nano tinted coating applied to surface NO.10 in order to reflect the sun's rays and keep them from heating up the CCF cavity. Finally, the fifth group of systems is nearly identical to the fourth group, with the exception of Surface No. 14 having an acrylic high-performance coating applied to it.

Table 2 displays the results of calculations made in the programme Window 7.7 to determine the performance characteristics of the CCF configurations that have been built. These characteristics include the thermal transmittance U-value, the solar heat gain coefficient SHGC-value, the solar transmittance T_{sol}, and the visible solar transmittance T_{vis}. The algorithms behind this programme were developed by the Lawrence Berkeley National Laboratory (LBNL) and are based on the international standards for the thermal and solar-optical performance of glazing systems, ISO 15,099 and ISO/EN 10,077.

Table 2's values are entered into EnergyPlus and DesignBuilder to evaluate the CCF setups in relation to a baseline SGU with a grey coating. When the incidence radiation level on the façade is less than 250 W/m^2, the integrated Venetian blinds are totally retracted, and when it reaches this threshold, the blinds automatically deploy.

Table 2
Simulation of CCF glazing configuration parameters for performance [16]

Groups	Glazing Configuration	U- value (W/m^{2}K)	SHGC	T_{sol}	T_{vis}
Baseline	SGU with gray coating	5.882	0.670	0.550	0.559
	CCFT1	1.219	0.588	0.447	0.633
Group 1	CCFT1- VB1	0.968	0.227	0.102	0.152
	CCFT1-VB2	0.973	0.238	0.032	0.041
	CCFT2	0.779	0.152	0.103	0.309
Group 2	CCFT2-VB1	0.656	0.065	0.023	0.070
	CCFT2- VB2	0.658	0.062	0.007	0.020
	CCFT3	0.822	0.200	0.147	0.414
Group 3	CCFT3-VB1	0.684	0.076	0.034	0.093
	CCFT3-VB2	0.687	0.066	0.009	0.026
	CCFT4	1.100	0.073	0.021	0.044
Group 4	CCFT4-VB1	1.101	0.113	0.032	0.066
	CCFT4- VB1’	1.101	0.154	0.042	0.086
	CCFT5	1.091	0.075	0.027	0.050
Group 5	CCFT5- VB1	1.092	0.116	0.042	0.074
	CCFT5- VB1’	1.092	0.158	0.056	0.096

2.2.2 Location and climate class

CCF technology validation took place in Penang, Malaysia. This implementation makes use of a weather data file that was created using the TMY/ISO 15927-4 processes and is based on 15 years of historical weather data (2003–2017) that was obtained from the Climate One Building website

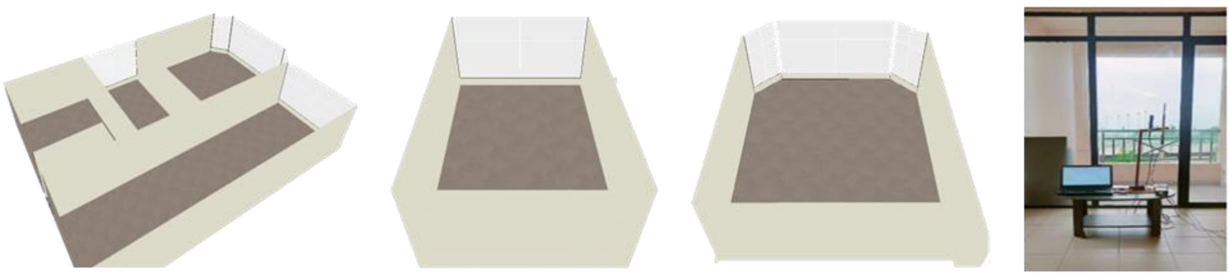
[24,25]. The monthly averages of outdoor air temperature (T_o), relative humidity (RH), and global solar radiation are shown in Table 3 of the weather data file.

Table 3
Climate data for the specified location [4]

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 apartment has three bedrooms, two bathrooms, a kitchen, and a living room. The spaces 1, 2, 3, and 4 were selected to be developed as a simulation model based on the four directions that are characterised by glazed facades and a high thermal atmosphere. So that the study takes place in all aspects of the building. Space 1 is on the building's third floor and is a medium bedroom with a floor area of 24 m^2. Space 2 is on the building's northern side and is a living room with a floor area of 26 m^2. Space 3 is on the building's western facade and is a middle bedroom with a floor area of 22 m^2. Additionally, space 4 is on the building's southern facade. However, living space measures 26 m^2; floor 20. The ceiling height in those areas is 2.85 m^2. Additionally, 85% of its outside walls are made up of glass and face the east, north, west, and south, respectively. As can be seen in Figure 3 and Table 4, a detailed apartment model has been constructed using actual apartment dimensions, materials, and openings.



Building A   Space 3 (west)   Space 2 (North)   Space 1 (East)

Fig. 3. The original building and room, as well as the created numerical model

Table 4
Materials used for the numerical model and their thermal properties [2,4,26]

Item	Description	Conductivity (W/m-k)	Total thickness (mm)	U-value (W/m^2-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

Figure 4 displays the results of a comparison between the T_i predicted by EnergyPlus using updated weather data and the T_i measured in the field between March 3rd and 8th, 2023. This comparison was undertaken to verify the accuracy of the constructed building model. The results show that the measured T_i and predicted T_i agree within a margin of error of only 1% on average. The accuracy of the predicted T_i, was further demonstrated by a correlation coefficient of around 0.95 [27].

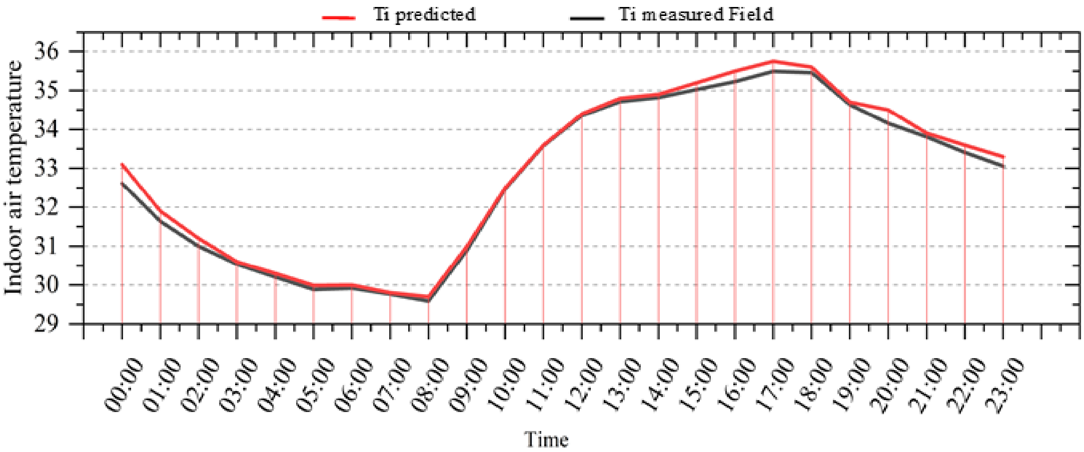


Fig. 4. T_i Predictions and Measurements: A Comparison

2.2.4 The CCF configurations performance modelling and simulation

Energy Plus 8.9.0 and DesignBuilder (v8.9) are two of the most innovative software packages for analysing building performance. That was used to model the building's interior climate and energy demands by factoring in the performance of the façade, the characteristics and activation settings of the integrated blinds, and the HVAC system configuration, among other things [28-30]. In consideration of that, four models were evaluated in each of the four directions of the facades, as shown in Table 1. While each model represents a single room with a single 85%-glazed facade, three people occupy the models for a full day, seven days a week.

According to CIBSE Guide A: Environmental Design, every occupant needs a 120-watt load [6]. A total of 50 watts per occupant is allotted for the use of electrical devices (laptops, phone chargers, etc.). Each model has an air conditioning system with a capacity of 1 tonne at a voltage of 220 volts, which occupants operate for at least 12 hours a day to achieve a balance between natural and mechanical ventilation within a range of between 18°C and 24°C. Additionally, the lighting system consists of LED lamps of not less than 500 lux (CIBSE, The SLL Lighting Handbook (2018)). However, in order to obtain accurate results commensurate with the concept of the new CCF façade and to achieve accurate comparisons before and after the installation of the CCF façade, all tests were conducted in an environment devoid of any mechanical ventilation. In addition, all glass façades were closed, whether in the measured field or simulation.

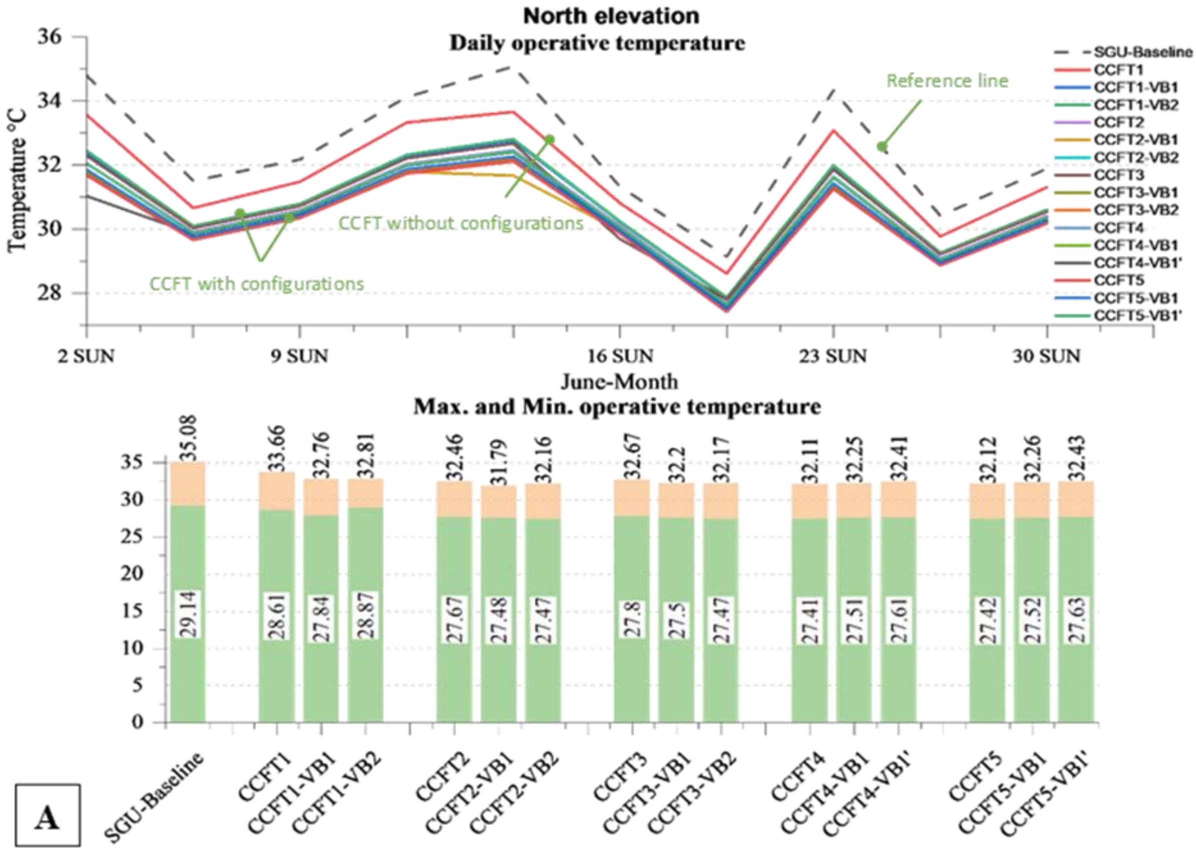
CCF simulations were accomplished in the Energy Plus programme using the factors (SHGC, T_{vis}, and U-value) as shown in Table 2 and Figure 2, respectively. That will help select the best classification for achieving the aforementioned factors (coating and venetian blind). In this study, we used operating temperature (indoor air temperature and radiant temperature) and relative humidity to evaluate thermal comfort monthly and annually across all models. After that, we performed the experiment on a monthly basis, choosing March for the east and west, June for the north, and January for the south, since these are the months with the highest radiant temperature ratios throughout the year.

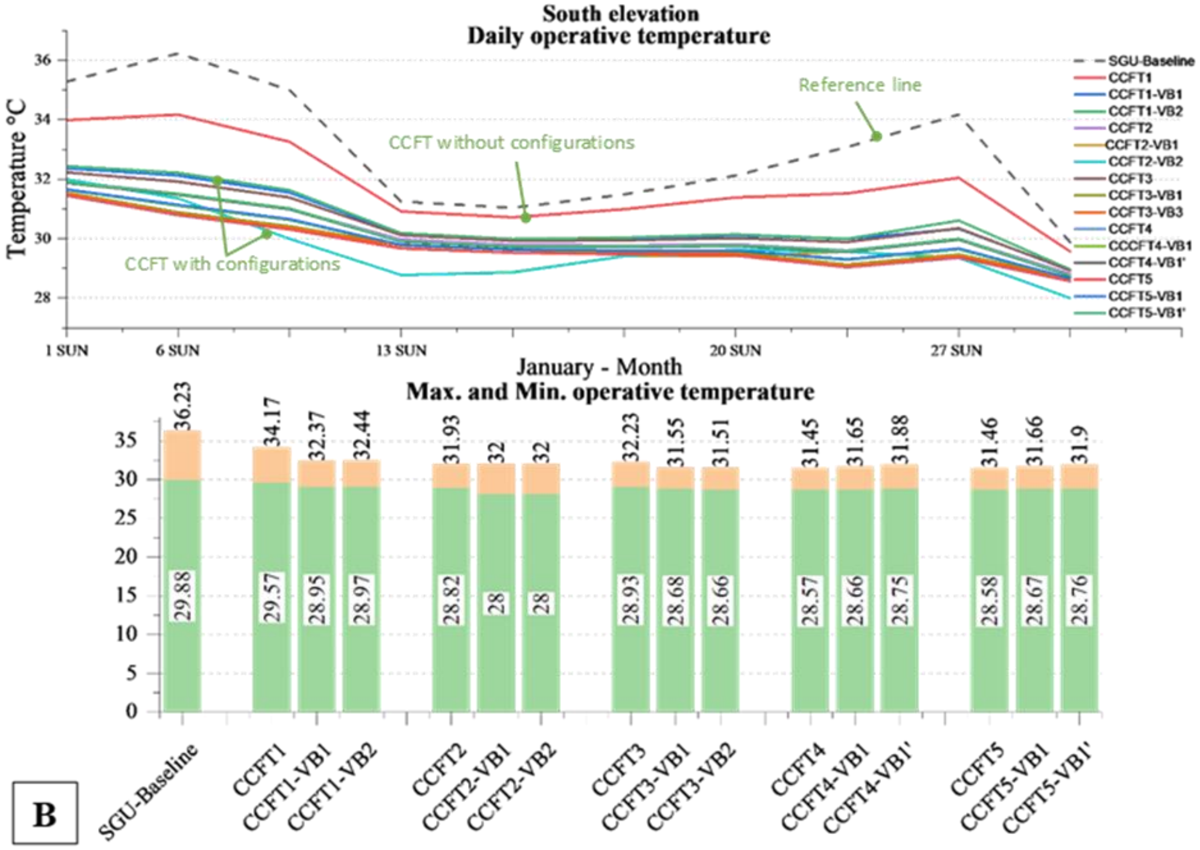
3. Results and Discussion

3.1 Effect of CCFTs Application on Peak Temperatures

3.1.1 CCF-TGU with configuration, monthly-round performance

The peak daily operating temperature of the CCFTs is shown in Figure 5 in comparison to the reference condition, which is when there is no CCFT present. According to the findings, the CCFT application revealed statistically substantial reductions in the daily peak operating temperature when compared to the condition that served as the reference. The average monthly operating temperature peak ranged between 31.79 and 27.48°C, which is lower than the reference case's 35.08°C on the northern façade. On the southern façade, the average monthly operating temperature peak ranged between 32 and 28°C, which is lower than the reference case's 36.23°C. It ranged from 32.34°C to 29.99°C in comparison to 35.91°C for the reference case at the eastern facade, and it ranged from 32.44°C to 29.83°C in comparison to 36.11°C for the reference case at the western facade.




South elevation
Daily operative temperature
Temperature °C
Reference line
CCFT without configurations
CCFT with configurations
SGU-Baseline
CCFT1
CCFT1-VB1
CCFT1-VB2
CCFT2
CCFT2-VB1
CCFT2-VB2
CCFT3
CCFT3-VB1
CCFT3-VB3
CCFT4
CCCFT4-VB1
CCFT4-VB1'
CCFT5
CCFT5-VB1
CCFT5-VB1'
1 SUN
6 SUN
13 SUN
20 SUN
27 SUN
January - Month
Max. and Min. operative temperature
36.23
34.17
32.37
32.44
31.93
32
32
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28.76
SGU-Baseline
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CCFT1-VB2
CCFT2
CCFT2-VB1
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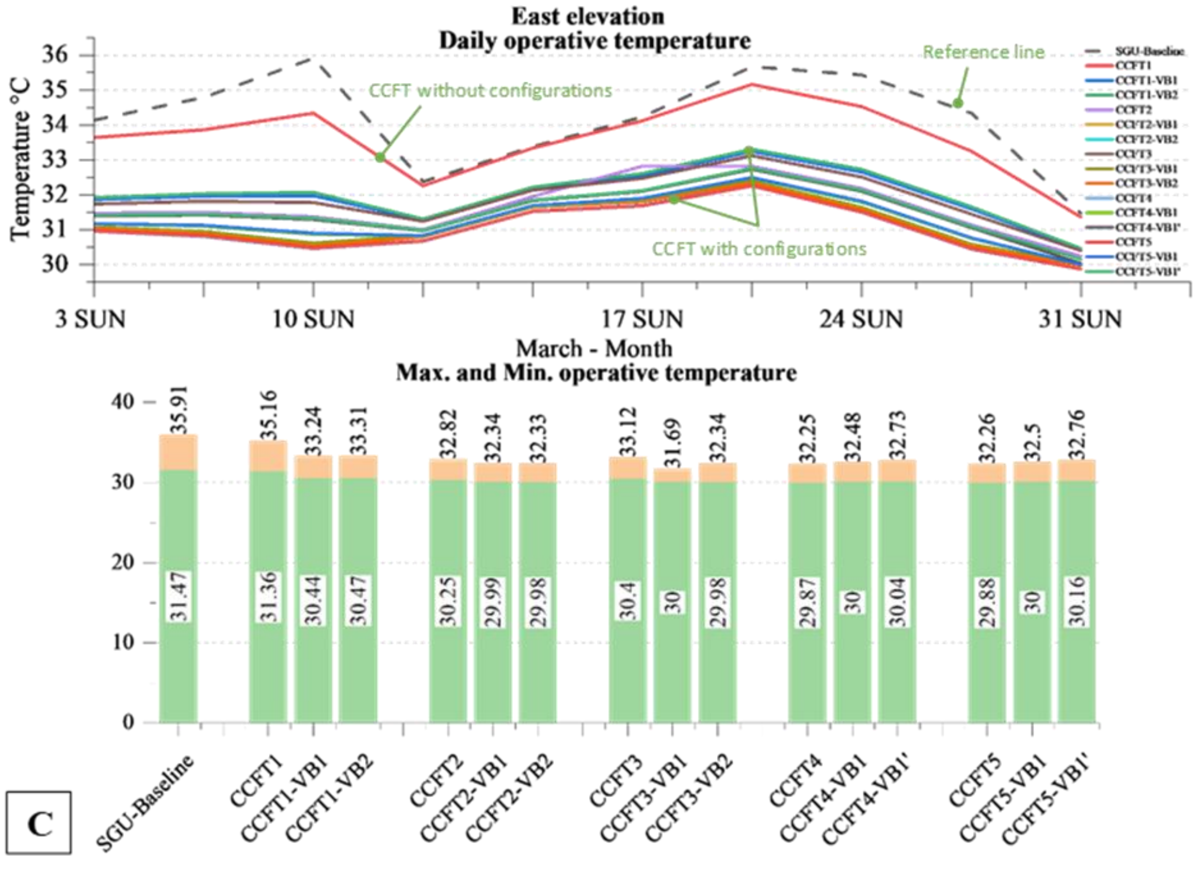
East elevation
Daily operative temperature
Temperature °C
Reference line
CCFT without configurations
CCFT with configurations
SGU-Baseline
CCFT1
CCFT1-VB1
CCFT1-VB2
CCFT2
CCFT2-VB1
CCFT2-VB2
CCFT3
CCFT3-VB1
CCFT3-VB2
CCFT4
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3 SUN
10 SUN
17 SUN
24 SUN
31 SUN
March - Month
Max. and Min. operative temperature
35.91
35.16
33.24
33.31
32.82
32.34
32.33
33.12
31.69
32.34
32.25
32.48
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31.36
30.44
30.47
30.25
29.99
29.98
30.4
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29.98
29.87
30
30.04
29.88
30
30.16
SGU-Baseline
CCFT1
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CCFT1-VB2
CCFT2
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CCFT2-VB2
CCFT3
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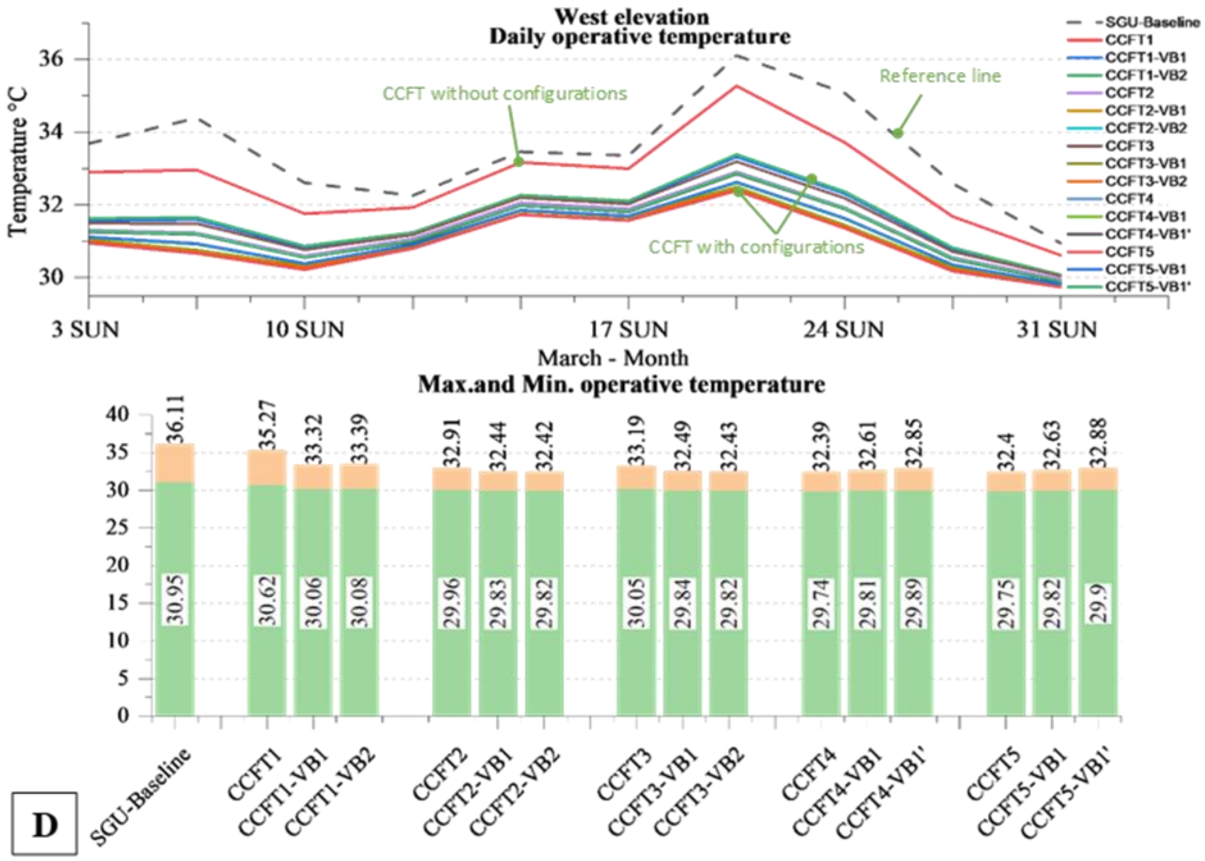

Fig. 5. shows the average daily and monthly highs and lows for each CCFT's north (A), south (B), east (C), and west (D) facades, respectively

CCFT2 and CCFT4, as illustrated in Figure 2 with integrated horizontal white Venetian blinds (VB1), were shown to be the most efficient CCF creations through simulation. For each of the four directions in the humid tropical Malaysian climate, Figure 6 in addition displays the percentage of quantitative efficiency (SGU / (SGU - CCF) * 100) compared to SGU at each facade. The ideal improvement for each group was determined by comparing the results obtained at their respective operating temperatures inside the environment. The northern facade has CCFT2 and CCFT4 values of 40-94% and 37-95%, respectively, while the southern facade has values of 46-89% and 52-83%, the eastern facade has values of 40-67% and 41-68%, respectively, and the western façade has values of 40-69% and 41-70%, respectively.

According to Table 2, the majority of the improvements with CCFT2 and CCFT4 can be attributed to the value of the SHGC when venetian blinds are integrated into the CCF cavity. CCF is more effective than SGU at reducing solar gain through the facade, with a SHGC value of 0.065 for CCFT2 with white venetian blinds and 53/23 LE coating and a SHGC value of 0.073 for CCFT4 with white venetian blinds and 83/58 LE nano coating, which, due to its humid tropical environment, where mechanical cooling is usual, contributes to energy consumption in a climate dominated by mechanical cooling. Reducing the need for cooling is the primary factor in the benefits brought about by CCFs [15,16].

Compared to the blinds with the darker coating (57/72 LE) in CCFT3, the lighter-coloured blinds and coating (53/23 LE) in CCFT2 demonstrate a slight boost in performance (1%). Also, in CCFT4, the effect is demonstrated by reducing the operating temperature of the blind colour and the type of glass coating; the light-coloured blinds and coating 83/58 nano coating demonstrate a slight performance improvement (approximately 1%) in comparison to the blinds with the darker coating

92/84 acrylic material. As seen in Figure 5 and Figure 6, the best facades for improving operational temperature are the southern, western, eastern, and then northern facades. This is due to the orientation and the ratio of thermal radiation, as the evaluation of the facades is based on the four directives and the month in which the radiative temperature ratio is highest.

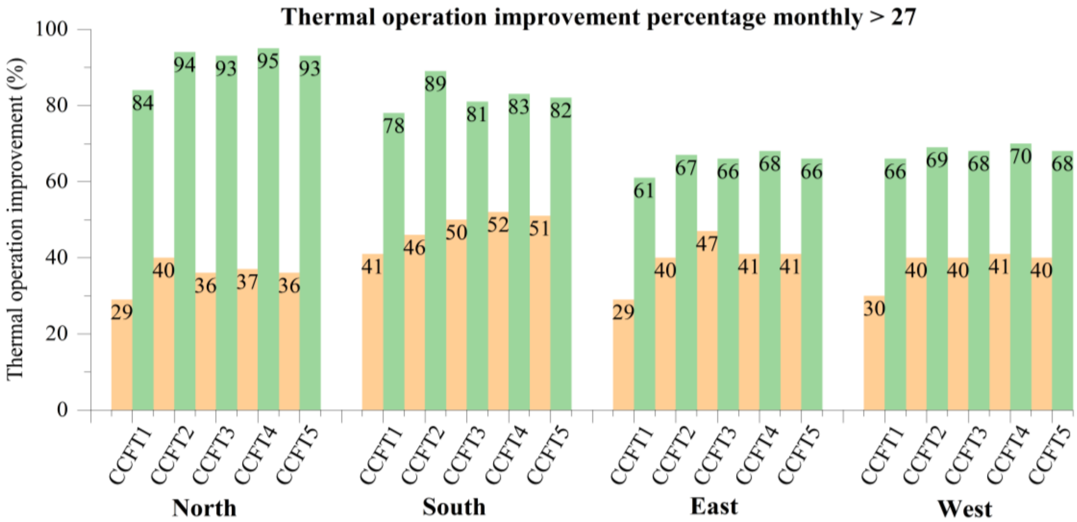

Fig. 6. Monthly-round daily means of the percentage of operating temperature enhancement for CCFT for the north, south, east, and west facades

3.1.2 CCF-TGU with configuration year-round performance

The performance and efficacy of CCF throughout the year were compared to baseline (SGU) (i.e., for operational temperature comparison). Figure 7 shows a year-round decline in the peak operating temperature for each of the evaluated facades; for example, the northern façade demonstrates a drop in maximum temperature of 3°C, from about 35.4 to 32.82°C, and a drop in minimum temperature of 1.5°C, between 28.98 and 27.84°C. This corresponds to an improvement rate of 31–90% and 33–91%, as shown in Figure 8 for the best two groups, CCFT2 and CCFT4, respectively. The highest limits on the southern façade show a decrease of 2°C, going from 34.17 to 32.17°C, and a decrease of 1.5°C in the lower limits, which ranged from 29.39 to 27.89°C. This represents an improvement rate of 33–89% for CCFT2 and 34–89% for CCFT4, respectively. The eastern façade showed a decrease of 4°C, approximately from 36.62 to 32.35°C in the maximum limits, and a decrease of 1.5°C in the lower limits, between 29.42 and 28.17 °C, with an improvement rate of 45-88% and 42-89% for the best two groups, respectively, CCFT2 and CCFT4. Additionally, the western facade demonstrates a decrease of 5°C in the highest limits, going from 37.03 to 32.62°C, and a decrease of 1.5°C in the lower limits, going from 29.22 to 28°C, with an improvement of 44-90% and 45-90% for CCFT2 and CCFT4, respectively.

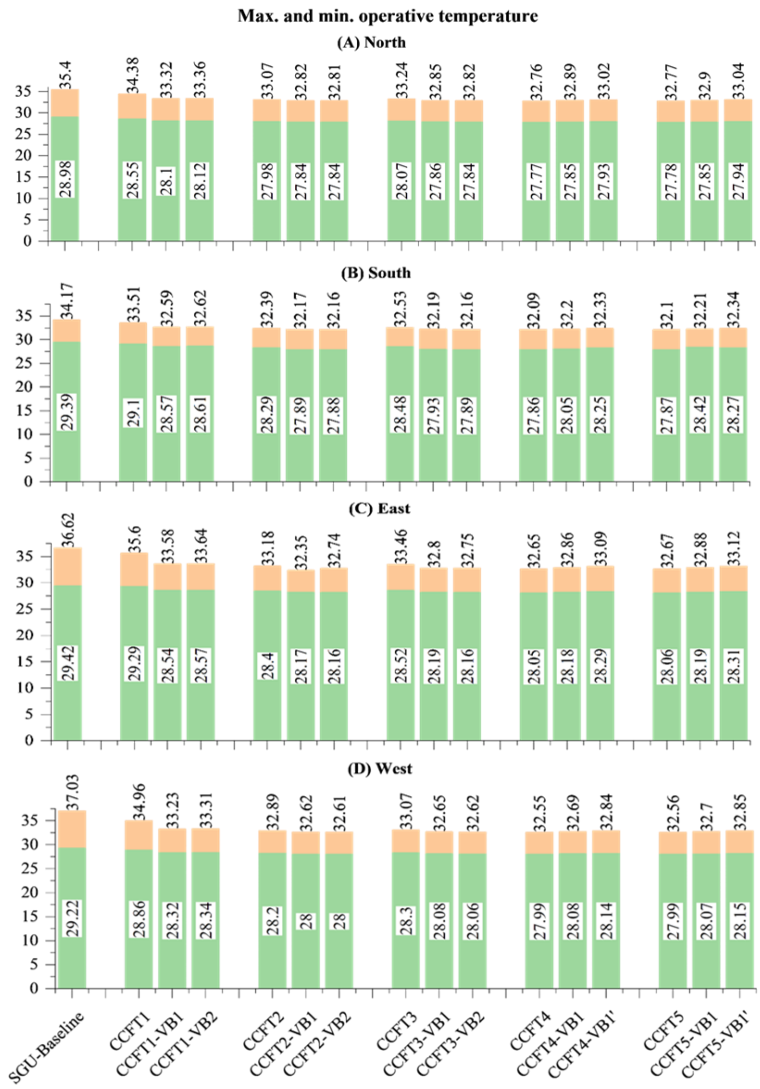

Fig. 7. shows the average annually highs and lows for each CCFT's north (A), south (B), east (C), and west (D) facades, respectively

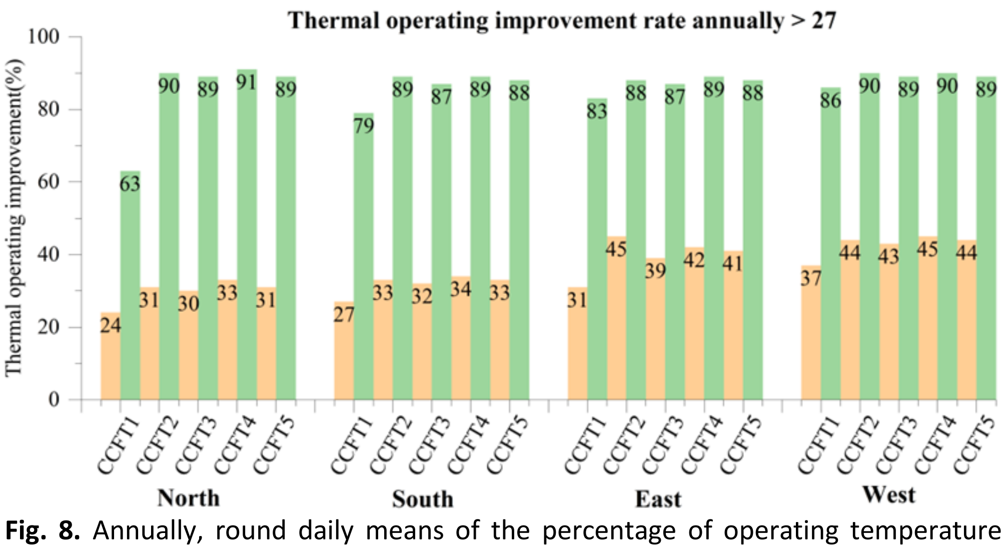

Fig. 8. Annually, round daily means of the percentage of operating temperature enhancement for CCFT for the north, south, east, and west facades

We observe that the maximum temperatures, which are > 27°C, decrease by 3 to 5°C in the maximum limits, i.e., within the range of 32 to 31°C, and the minimum temperatures, which are 27 °C, decrease by 1 to 2°C. And that achieved the thermal comfort limits for the internal environment for operating temperatures (internal temperature + radiant temperature), as stated by the researcher in a previous study [6,16]. That results in a reduction in the cooling load in a climate dominated by the use of mechanical cooling due to the humid tropical climate, which reduces energy consumption by up to 25% to 35% to achieve thermal comfort for passengers without consumption by mechanical systems [15]. As can be seen in Figure 5, Figure 7, and Figure 8, the western facade is most improved, followed by the eastern facade, the northern facade, and then the southern facade. This is due to the orientation and the ratio of thermal radiation.

The majority of the enhancements with CCFT2 and CCFT4 are attributable to the value of the SHGC when venetian blinds are incorporated into the CCF cavity, as shown in Table 2. An SHGC value of 0.065 for CCFT2 with white venetian blinds and 53/23 LE coating, and a SHGC value of 0.073 for CCFT4 with white venetian blinds and 83/58 LE nano coating.

Compared to the blinds with the darker coating (57/72 LE) in CCFT3, the lighter-coloured blinds and coating (53/23 LE) in CCFT2 demonstrate a slight boost in performance (1%). In addition, in CCFT4, the effect is demonstrated by reducing the operating temperature of the blind colour and the type of glass coating; the light-coloured blinds and coating 83/58 nano coating demonstrate a slight performance improvement (approximately 1%) in comparison to the blinds with the darker coating 92/84 acrylic material.

Comparing this study to previous studies, as shown in Table 5, we find that this study was conducted in Malaysia in a humid tropical climate by studying all the orientations of the facades separately and focusing from accurate to finer, so that it began with the highest months and then moved on to the annual average [15,16,31]. The monthly improvement rate for the operating temperature of the northern facade was 38.5–94.5%, the operating temperature of the southern facade was 49–86%, the operating temperature of the eastern facade was 40.5–67.5%, and the operating temperature of the western facade was 40.5–69.5%. Furthermore 38.5%–90% improvement rate for the annual temperature of operation.

Previous research was conducted in a closed room with three open sides (south, east, and west) in nine distinct cities (Rio de Janeiro, Dubai, Sydney, New York, Shanghai, London, Toronto, Beijing, and Helsinki) on an annual basis. Achieved a thermal comfort rate between 68 and 89%.

According to all investigations, the optimal combination of CCF is CCFT2 with a 53/23 LE coating. The current study also demonstrated the quality of results obtained by the CCFT4 group with 58/83 nanocoating with silver reflector in a humid tropical climate, as recommended by other researchers [32-35]. In addition, Table 5 reveals that the percentage of improvement in the studies is very close to the annual results; however, this study revealed a relatively greater improvement in the 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 with the best results
The current study	Penang - Malaysia	Tropical – humidity	North South East West	38.5 – 94.5 % 49 - 86 % 40.5 – 67.5 % 40.5 – 69.5 %	38.5 – 90 %	CCFT2 with E-low coating 53/23LE and CCFT4 with Nano coating 83/58
Previous studies [15,16,31]	Rio de Janeiro Dubai Sydney New York Shanghai London Toronto Beijing Helsinki	Tropical savanna Dry desert hot Temperature humidity Temperature humidity Temperature humidity Temperature oceanic Continental hot – summer humid Continental monsoon - influenced Continental warm – summer humid	A room with three open sides, south, east, and west	N/A	68 – 89 %	CCFT2 with E-low coating 53/23 LE

4. Conclusions and Future Work

The new CCF affects thermal comfort (operating temperature). Design Builder, EnergyPlus, and Windows 7.8 tested SGU and CCF combinations in a tropical-humidity climate. The performance analysis shows that CCFs provide greater thermal comfort than SGUs with grey coatings. Conclusions are:

(i) The operational temperature peaks that were studied were effectively reduced using CCFs.
(ii) Two sets of CCFT2 with a 53/23 LE coating and CCFT4 with an 83/58 LE nanocoating were used to obtain the highest reduction in peak operating temperature.
(iii) In terms of passenger comfort, CCFT2 and CCFT4 demonstrated effective performance all year long, with a maximum annual decrease of 3 to 5°C in peak operating temperature and a minimum annual decrease of 1 to 2°C.

Finally, compared to the baseline SGU, each CCF system option improved peak operative temperature by 38.5 to 90% to achieve thermal comfort. Tropical climates with high relative humidity showed this improvement. This was made possible by installing Venetian blinds in the coatings and using specially coated glass. Energy usage rises in regions where cooling is primary; hence, CCF is implemented to mitigate the heat gain from the sun entering a building's face. This research also found that using lighter-coloured blinds or a coating with a ratio of 53/23 (T_{vis}/T_{sol}) and 83/58 nano coating on the glass surface rather than 72/57 LE or 92/84 acrylic improves performance by about 1%.

In addition to its findings, this study raised new research questions, such as how to validate simulated CCF, how to investigate overheating in the CCF cavity, and how to analyse CCF's performance with varying blind control strategies and slat angles.

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