UNIVERSITI PUTRA MALAYSIA

POTENTIAL OF HARNESSING INCIDENT SOLAR ENERGY IN BUILDING SHADING DEVICE FOR THERMAL APPLICATION

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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POTENTIAL OF HARNESSING INCIDENT SOLAR ENERGY IN BUILDING SHADING DEVICE FOR THERMAL APPLICATION

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February 2018

Chair: Nor Mariah Adam, PhD, P Eng
Faculty: Engineering

The recent trend of integrating a solar energy system in building has become a sustainable solution for energy conservation. This work proposed an alternative philosophy of solar absorber system, which is harnessing the incident solar energy on the building shading device. The existing literature mainly discussed the performance of shading devices in term of expelling solar incident ray, excluding the potential of energy collection. There is limited investigation on the energy harnessing through shading device under the tropical skies. Besides, most of the building integrated solar thermal models were developed and studied in higher latitude regions. The overall objective of this work is to develop a shading façade-integrated solar absorber system model and assess its performance under the hot tropical climate. Mathematical considerations of solar radiation model, shading façade-integrated solar absorber geometrical model and solar absorber model were resolved holistically in a segregated manner using MATLAB programming environment. The orientation, geometrical and thermal characteristics of the system model were analysed and assessed to configure the system model optimally. Numerical results showed that the optimum tilt angle of the shading façade-integrated solar absorber for maximum solar radiation interception was approximately 15^{o}. According to the geometrical and thermal performance analyses, the configuration of two solar plates system with the dimensions of plate-to-cover spacing of 10 mm, plate thickness to width ratio of 0.15 and tube centre-to-centre distance of 8.2 cm was the optimum option. It has resulted in the maximum effective area of exposure to solar ray, minimum overall heat loss coefficient and optimum heat removal factor valued at 98.9%, 8.5951 W/(m^2K) and 0.898, respectively. A prototype of the complete system model was fabricated according to the outcomes of the numerical simulations. To confirm its performance, outdoor experiments were conducted in daytime for 139 days under the actual tropical sky. The outdoor field test has demonstrated that the system model was principally dependent on the available global irradiance and its performance was impaired by the high occurrence of afternoon rain. On average, the system model was capable to achieve the daily system efficiency of 50.5%, maximum daily water temperature attained at 48.9 ºC and solar water heating rate of 2.9 ºC/hr. Findings showed that the system model could perform most frequently at the daily system efficiency ranging from 45% to 60% and the maximum daily water temperature attained from 45 ºC to 57 ºC during the test period. Under the stagnant condition, the measured maximum temperatures of glass surface and absorber plate surfaces were 74.3 ºC and 102.9 ºC, respectively. Verification of results for the simulation and experimental data measurement were conducted; and they were in agreement.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

POTENSI PENGUMPULAN TENAGA SURIA TUJU DARIPADA PERANTI TEDUHAN BANGUNAN UNTUK APLIKASI HABA

Oleh

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Februari 2018

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Faculti: Kejuruteraan

Tren kebelakangan ini yang menyepadukan sistem tenaga suria pada bangunan telah menjadi satu penyelesaian yang mampan untuk pengabadian tenaga. Kajian ini mencadangkan satu falsafah alternatif sistem pengumpul suria untuk mengumpul tenaga suria tuju daripada peranti teduhan bangunan. Kajian literatur yang sedia ada kebanyakannya membincangkan prestasi peranti teduhan dari segi pemantulan sinaran suria yang tidak mengambil kira potensi untuk pengumpulan tenaga. Literatur kawasan berkaitan tropika adalah sangat kurang walaupun potensinya yang menarik. Objektif keseluruhan kerja ini adalah untuk membangunkan satu model sistem pengumpul suria bersepadu teduhan di kawasan tropika dan menilai prestasinya. Pertimbangan matematik atas model radiasi suria, model geometri pengumpul suria bersepadu teduhan dan model pengumpul suria telah diselesaikan secara menyeluruh dengan cara yang berasingan menggunakan sekitaran pengaturcaraan MATLAB. Orientasi facade bangunan, ciri-ciri geometri dan termal bagi model sistem telah dianalisis dan hasilnya dinilai untuk mewujudkan model sistem secara optimum. Keputusan berangka menunjukkan bahawa sudut kecondongan optimum pengumpul suria bersepadu teduhan untuk maksimum pemintasan radiasi suria adalah hampir 15°. Menurut analisis prestasi geometri dan haba, konfigurasi sistem dua plat suria dengan dimensi yang berukuran jarak 10 mm di antara plat dan penutup, 0.15 nisbah ketebalan plat kepada lebar plat dan jarak 8.2 cm di antara tiub-tiub adalah pilihan optimum. Ia telah menghasilkan keberkesanan luas pendedahan kepada sinar suria yang maksimum, pekali kehilangan haba keseluruhan yang minimum dan faktor penyingkiran haba yang optimum, dengan masing-masing bernilai 98.9%, 8.5951 W/(m^2K) dan 0.898. Satu prototaip model sistem yang lengkap telah dibina mengikuti hasil simulasi berangka. Untuk mengesahkan prestasinya, eksperimen telah dijalankan pada siang hari selama 139 hari di bawah langit tropika. Hasil eksperimen menunjukkan bahawa model sistem pada dasarnya adalah bergantung kepada sinaran global yang tersedia dan prestasinya telah terjejas oleh kekerapan hujan yang tinggi pada sebelah petang. Secara purata, model sistem ini mampu mencapai kecekapan sistem harian pada

50.5%, suhu air maksima pada 48.9 ºC dan kadar pemanasan air pada 2.9 ºC/jam. Penemuan kajian menunjukkan bahawa model sistem itu dapat menunjukkan prestasi dengan kecekapan sistem harian daripada 45% hingga 60% dan suhu air harian maksima daripada 45 ºC hingga 57 ºC dengan kekerapan yang tertinggi dalam tempoh ujian. Di bawah keadaan mantap, suhu maksima yang diukur pada permukaan kaca dan permukaan plat penyerap adalah masing-masing 74.3 ºC dan 102.9 ºC. Pengesahan keputusan simulasi dan pengukuran data eksperimen telah dijalankan. Model simulasi pada dasarnya adalah bersamaan dengan eksperimen.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF SYMBOLS

A_c	Collector area (m^2)
A_e	Area of the edge (m^2)
A_{exp}	Effective area of louvre plate exposure to solar ray per unit length (mm^2/mm)
A	Internal cross-sectional area of pipe (m^2)
b	Bond width (mm)
c	Distance between two louvre plates (mm)
c'	Gap between the static solar plate arrays (mm)
C_b	Bond conductance (W/(m K))
C_p	Specific heat of fluid (J/ (kg K))
d	Horizontal extension (mm)
D'	Fraction of beam solar radiation on an inclined surface to total radiation on a horizontal surface (dimensionless)
D	Tube outer diameter (mm)
D_i	Tube inner diameter (mm)
E_{total}	Daily total energy collected (J)
E	Daily net energy saving (kWh)
F_R	Heat removal factor (dimensionless)
F''	Collector flow factor (dimensionless)
F	Fin efficiency or Fin factor (dimensionless)
F'	Collector efficiency factor (dimensionless)
g	Gravitational constant (m/s^2)
G_{on}	Extraterrestrial radiation incident on a plane normal to radiation (W/m^2)
G_{sc}	Solar constant (W/m^2)
G_o	Extraterrestrial radiation incident on a horizontal plane (W/m^2)

G_{avg}	Average daily global irradiance (W/m^2)
G	Global irradiance (W/m^2)
Gr	Grashof number (dimensionless)
H_o	Daily extraterrestrial radiation incident on a horizontal surface (J/m^2)
$\bar{H}_o$	Monthly average daily extraterrestrial radiation incident on a horizontal surface (J/m^2)
$\bar{H}$	Monthly average daily radiation on a horizontal surface (J/m^2)
$\bar{H}_d$	Monthly average daily diffuse irradiation on a horizontal surface (J/m^2)
H_d	Daily solar radiation of the test day (J/m^2)
H_s	Seasonal average daily solar radiation (J/m^2)
$\bar{H}_T$	Total monthly average daily solar radiation on a tilted surface (J/m^2)
h	Plate thickness (mm)
h_w	Wind convection heat transfer coefficient (W/(m^2 K))
$h_{r,c-a}$	Radiation heat transfer coefficient from cover to ambient (W/(m^2 K))
$h_{c,p-c}$	Convection heat transfer coefficient between plate and cover (W/(m^2 K))
$h_{r,p-c}$	Radiation heat transfer coefficient from plate to cover (W/(m^2 K))
$h_{r,b-a}$	Radiation heat transfer coefficient from bottom to ambient (W/(m^2 K))
h_{b-a}	Convection heat transfer coefficient between bottom and ambient (W/(m^2 K))
$h_{r,e-a}$	Radiation heat transfer coefficient from edge to ambient (W/(m^2 K))
h_{e-a}	Convection heat transfer coefficient between edge and ambient (W/(m^2 K))
h_{fi}	Heat transfer coefficient between fluid and tube wall (W/(m^2 K))
I_o	Daily extraterrestrial radiation incident on a horizontal surface for a specific period between hour angles (J/m^2)
I	Direct current (A)
$\bar{K}_T$	Monthly average daily clearness index (dimensionless)

k_a	Thermal conductivity of air (W/(m K))
k_b	Bottom insulation thermal conductivity (W/(m K))
k_b'	Bond thermal conductivity W/ (m K)
k_e	Edge insulation thermal conductivity (W/(m K))
k_{fi}	Thermal conductivity of fluid (W/(m K))
k_p	Plate thermal conductivity (W/ (m K))
L_{loc}	Longitude of location (degree)
L_{st}	Standard time zone meridian (degree)
l	Plate length (mm)
l_b	Shaded area per unit length of a louvre plate (mm^2/mm)
L_{p-c}	Plate-to-cover spacing (mm)
$\dot{m}$	Total mass flow rate of collector (kg/s)
M	Water mass in storage tank (kg)
num	Number of day of the year
n	Number of louvre plate
Nu	Nusselt number (dimensionless)
P_r	Prandtl number (dimensionless)
Q_u	Actual useful energy gain (W)
$\bar{R}$	Ratio of the total monthly average daily solar radiation on an inclined surface to that on a horizontal surface (dimensionless)
R'	Thermal resistance value (m^2 K/ W)
R^2	Coefficient of determination (dimensionless)
R	Correlation coefficient (dimensionless)
Ra	Rayleigh number (dimensionless)
Re	Reynolds number (dimensionless)
S	Solar energy absorbed by absorber plate (W/m^2)

S_h	Height of the shaded opening below the horizontal shading façade (mm)
T_a	Ambient temperature (ºC)
T_c	Cover temperature (ºC)
T_b	Bottom temperature (ºC)
T_p	Absorber plate temperature (ºC)
T_{fi}	Inlet fluid temperature (ºC)
T_{fo}	Outlet fluid temperature (ºC)
T_m	Mean temperature of the medium (ºC)
T_w	Tube wall temperature (ºC)
T_F	Final temperature in storage tank after the test finishes (ºC)
T_I	Initial temperature in storage tank when the test starts (ºC)
$T_{\max}$	Maximum daily water temperature (ºC)
$\dot{T}$	Rate of temperature raised (ºC/hr)
U_L	Overall heat loss coefficient (W/(m^2 K))
U_t	Top loss coefficient (W/(m^2 K))
U_b	Bottom loss coefficient (W/(m^2 K))
U_e	Edge loss coefficient (W/(m^2 K))
V	Velocity (m/s)
V'	Direct voltage (V)
W	Tubes centre to centre distance (mm)
w_p	Plate width (mm)
Δx_b	Thickness of bottom insulation (mm)
Δx_e	Thickness of edge insulation (mm)

Greek symbols

δ	Declination angle (degree)
β	Slope (degree)
$\beta_{z,noon}$	Slope of the frontal surface of absorber at noontime (degree)
β_{opt}	Optimum plate slope (degree)
ϕ	Latitude of location (degree)
θ	Angle of incidence of beam radiation (degree)
γ	Surface azimuth angle (degree)
γ'	Average bond thickness (mm)
γ_s	Solar azimuth angle (degree)
α_p	Profile angle (degree)
α_s	Solar altitude angle (degree)
θ_z	Zenith angle (degree)
ρ_g	Ground reflectance factor (dimensionless)
ρ	Density of fluid (kg/m^3)
ω	Hour angle (degree)
ω_{ss}	Sunset hour angle for beam radiation on an inclined surface (degree)
ω_{sr}	Sunrise hour angle for beam radiation on an inclined surface (degree)
ω_s	Sunset hour angle (degree)
σ	Stefan–Booltzmann constant ($W/(m^2\ K^4)$)
α	Thermal diffusivity of air (m^2/s)
β'	Thermal expansion coefficient of air (1/K)
ε_p	Emittance of plate (dimensionless)
ε_c	Emittance of cover (dimensionless)
μ	Dynamic viscosity ($kg/(m \cdot s)$)

ν	Kinematic viscosity of air (m^2/s)
ν_f	Kinematic viscosity of fluid (m^2/s)
δt	Plate thickness (mm)
η	Daily system efficiency (%)

CHAPTER 1

INTRODUCTION

1.1 Background

Improving quality of life has accelerated the demand for energy consumption. It is associated with the expending of fossil fuels that are still dominating the present energy market share and challenging its sustainability. To address the current issue, green energy concept has served as a key direction of research and development universally in diminishing the impact of the conventional energy practices such as energy efficiency, sustainable energy alternatives and environmental conservation (Fernando et al., 2015).

Malaysia is a country that lies geographically in the equatorial zone, is accessible to plenty of solar insolation. The solar radiation on ground is about 400 MJ/m^2 to 600 MJ/m^2 monthly or 4 kWh/m^2 to 5 kWh/m^2 per day with average sunshine duration of 4 to 8 hours (Mekhilef et al., 2012). The figures have shown the amount of this natural available energy reaching on an outdoor exposed object is abundant. Due to this fact, Malaysia is commonly recognised by researchers as a potential nation to promote solar energy technology, in which solar thermal energy is oriented mostly in the systems (Oh et al., 2010). Solar thermal presents a prospective outlook in green energy initiative which would contribute about RM 3023 million of energy value per annum (Zamzam et al., 2003).

Building as the marking of human civilisation, has been identified as one of the largest energy consumers. A study shows the building sector has contributed to about 40% of the global energy expenditure due to the modern living standards (Tyagi et al., 2012). In Malaysia, the buildings consume for approximately 13% of the total energy consumption and 48% of electricity spending (Al-Mofleh et al., 2009). Similar to other hot climate countries, a considerable amount of energy has been used for maintaining the desirable indoor space thermal comfort and domestic hot water with the trend of rising incessantly. Out of the total energy use in building, roughly 55% is accounted under the consumptions by heating, ventilation and air conditioning units (Al-Abidi et al., 2012). The statistics clarifies the need of energy in building is mandatory, thus efforts to deal with energy in sustainable form to improve the thermal performance of the buildings are imperative for green building progress.

For the building thermal loads, solar heat can be accounted into energy share in two contexts, which are solar gain attenuation and solar thermal applications (D'Antoni and Saro, 2012). The practice of insulating the building or blocking the incident sunray has been adopted as the primary passive solution in the design stage to optimise the energy consumption. Efforts have been conducted on the building facades with thermal barrier property. In solar heating system, solar thermal collector is ordinarily known as a reliable green product to harness the solar energy. Building integrated solar energy system attracts much attention presently due to the progress of green concept, in which the integration has been carried out on various building facades such as wall, window, roof, gutter, balcony, awning and shutter. The current trend has indicated the importance of solar thermal integration in façade for future need in sustainable building approach (Chemisana et al., 2013; Chou et al., 2016; Motte et al., 2013a, 2013b; Yang et al., 2013).

1.2 Problem Statement

As the nation is positioned in the region of hot humid tropical climate, it possesses abundant supply of solar radiation on the ground throughout the year with less seasonal effect variation. Despite solar energy is one of the largest renewable energy sources, it has not been fully harnessed and utilised with regard to its potential in building specifically in this climatic zone. The statistics elucidate the energy need in building remains demanding, thus, it is a need to utilise the available energy around the building in a sustainable manner. The utilisation of solar thermal systems suggests a good approach towards sustainable building concept by converting the available solar thermal energy on the modern building facades to more valuable forms economically (Kostic and Pavlovic, 2012; Mammoli et al., 2010).

Several researchers have examined the solar radiation in the country (Eltbaakh et al., 2013; Khatib et al., 2012; Ng et al., 2012; Sopian and Othman, 1992; Sulaiman et al., 1999; Wan Nik et al., 2012); in brief, the previous works were carried out using various techniques to analyse and measure the solar intensity and solar behaviour without concerning the orientation factor in specific. The investigation of the solar intensity at different azimuth and tilt angles is very few in the equatorial tropics despite of its attractive potential in the concept of solar collector–façade integration. Most studies were reported at the middle and high latitudes that might not be applicable in the context of low-latitude regions featuring the relatively less seasonal variation (Jafarkazemi and Saadabadi, 2013; Talebizadeh et al., 2011). As a “rule of thumb”, the south-facing surface offers better solar energy collection for the regions placed in the northern hemisphere and vice-versa (Nieuwoudt and Mathews, 2005; Panchal and Shah, 2012; Pardhi and Bhagoria, 2013). In the region of low latitude, however, the scenario may not be similar. The sun tilts to both southern and northern skies of the site with a more uniform period in one year. Therefore, for the low-latitude region, despite of its location at the northern hemisphere, the north-oriented surface can potentially intercept a prominent amount of solar irradiance. It leads to a rational hypothesis that the north-facing components can receive a reasonable amount of solar radiation energy.

In recent years, the trend of adopting the integrated solar energy systems in building has become a sustainable solution following the rapid growth in building energy consumption. In term of architectural appearance and building plane, a study has identified that the building façade-integrated solar collector is of great importance to utilise solar energy optimally (Shi et al., 2013). Literature has presented the integration of solar energy model in numerous building facades to investigate its thermal performance and its importance was reasoned. An increase of thermal collection area by this manner could compensate the limitation of a standard solar collector in the best installation position (Xuan et al., 2012). It is essential to identify an alternative position for capturing the free solar thermal as a study shows there are about 20% of the residential buildings facing architectural restraints to install the solar thermal units (Mekhilef et al., 2012). Besides, adoption of solar collector integrated in building can be associated with heat removal from building envelope by the mean of heat convection. It presents a prominent scheme for cutting down indoor cooling demand, most effectively in hot regions (D'Antoni and Saro, 2012). The integration of solar energy systems on the building could improve the insulation features, establish an active building envelope energy production in attachment to solar energy utilisation (Furundzic et al., 2012). Overview the aforementioned remarks, integrating the solar thermal collection model into the building facades could upgrade the façade to be multifunctional that is not merely cutting down the solar gain but producing sustainable energy source as the main focus of this work.

Due to visual comfort, using fenestration system in architectural style is increasingly apparent. Nevertheless, clear glass could transmit over 75% of incident solar radiation into the indoor space of building (ASHRAE, 2009). Researchers have been concerning this subject with connotation to lower the solar irradiance from entering the buildings by means of shading philosophy. Report from ASHRAE (2009) expressed that the attachment of shading product on fenestration could shrink solar heat gain by as much as 80%, showing its high energy performance. The literature has widely acknowledged and attested the importance of shading device in building energy saving (Bellia et al., 2013; Cheng et al., 2013; Palmero-Marrero and Oliveira, 2010). It is particularly crucial in tropical and arid regions (Al-Shareef et al., 2001).

The existing literature mainly discussed the performance of shading devices in term of solar heat blockage for energy saving and daylight comfort, excluding the potential of energy collection from the components. Several research efforts related to the shading façade-integrated solar energy system were made, however, the investigation on the energy production by shading device is yet limited and at the early stage (Chou et al., 2016; Mandalaki et al., 2012; Palmero-Marrero and Oliveira, 2004, 2006, 2008; Sun and Yang, 2010). The value of its overall thermal quality remains undefined. Besides, most of the building integrated solar thermal models were developed and studied in higher latitude regions over 10^{o} N (Chemisana et al., 2013; Chou et al., 2016; Motte et al., 2013b; Palmero-Marrero and Oliveira, 2008; Ramirez-Stefanou et al., 2011). Investigation in the equatorial tropics is rare despite of its attractive potential.

Two preliminary field observations have been conducted to demonstrate a proof of concept to further strengthen and support the viability of this research. For the first field study, the solar irradiance for the month of March 2013 was measured under the actual tropical sky at latitude of 2^{o} 58’ N, longitude of 101^{o} 44’ E and elevation of 69 m. Figures 1.1 to 1.2 show the measured global solar irradiance in two sampling days.

The curves present an intermittent global solar irradiance profile due to the irregular cloud blockages and short afternoon rain. The weather trend has been confirmed showing the similar solar pattern to the previous field data collected at the same location during June 2010 till October 2010 (Ng, 2011). Despite the fluctuations, the solar irradiance reaches a peak during the solar noon period with the value of exceeding 900 W/m^2. This demonstrates that the location is capable of offering an encouraging amount of incoming solar energy source.

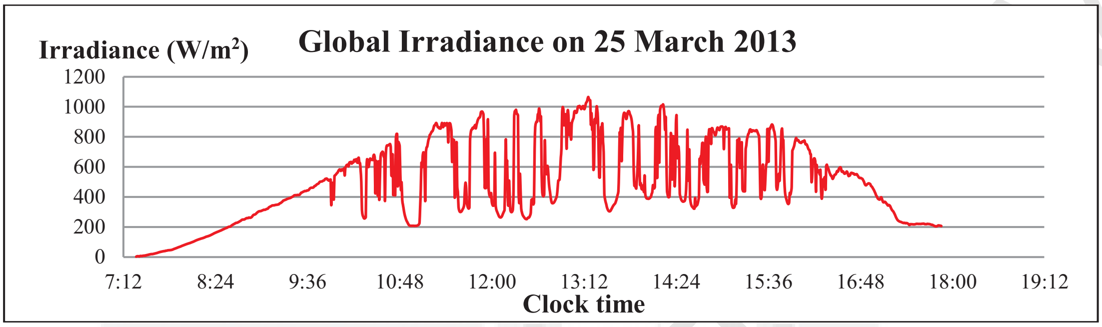

Figure 1.1: Global irradiance on 25 March 2013

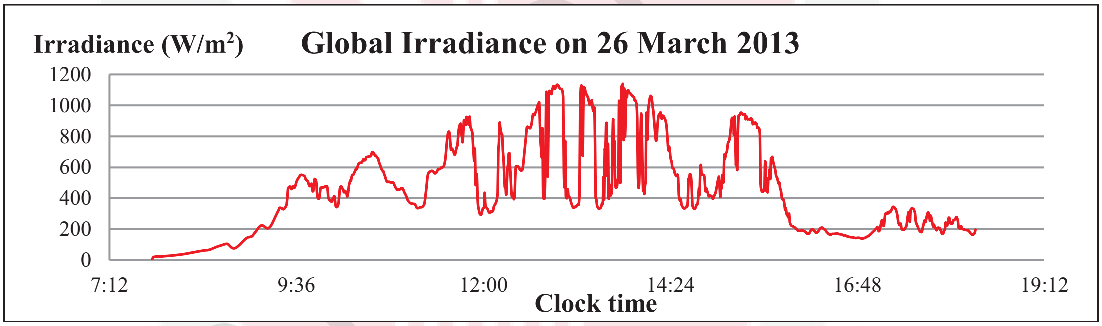

Figure 1.2: Global irradiance on 26 March 2013

Second observation has been carried out at the Engineering Faculty of UPM, located at the same region of the test field, to examine the fenestration and shading facades under the exposure of solar irradiance. Figures 1.3 and 1.4 present the results of thermographic analysis. Through the detail examination using thermal imager, the facades are obviously exposed to solar heat, absorbing a prominent amount of solar thermal energy although the structures are not meant for heat collection. The maximum surface temperature of the fenestration unit without shading facade could go beyond 44°C. For a site using shading facades, the solar irradiance has been attenuated leading to a relatively high surface temperature of shading facade with maximum value of over 46°C. The results have supported the previously stated literary notes. From the observations, these areas might be an imperceptible platform to harness solar thermal energy. It does not require extra space for the solar thermal collector installation. The evidence suggests a solar thermal integral unit could be a part of the shading structure.

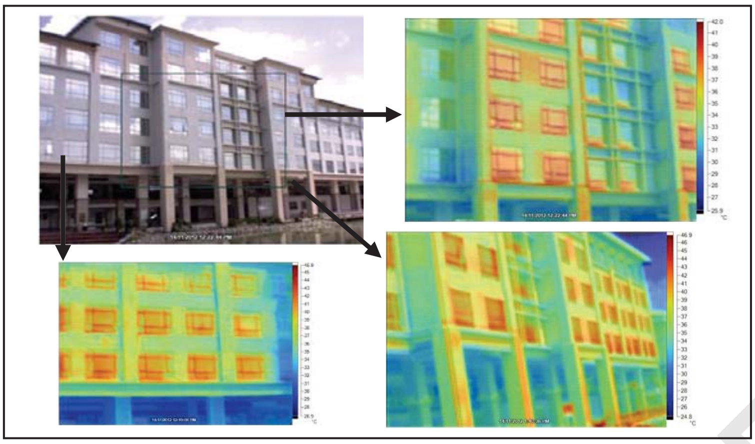

Figure 1.3: Thermographic images of fenestration structures under the exposure of solar irradiance on 3 May 2013

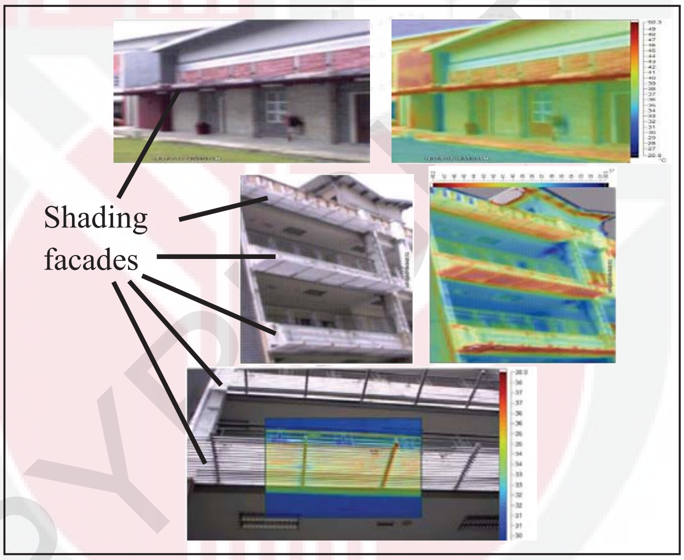

Figure 1.4: Thermographic images of shading devices under the exposure of solar irradiance on 3 May 2013

After reviewing the literature, it is found that the previous literature has lacked the following issues generally:

(i) Investigation on the façade orientation and solar radiation relationship for low latitude region below latitude of 10° N.
(ii) Literature lacks the study on the shading façade-integrated solar thermal collector in both theoretical and experimental analysis.
(iii) Geometrical characterisation of the solar thermal based shading façade.
(iv) Investigations of the thermal performance of the shading façade-integrated solar thermal collector under hot tropical climates.

Addressing these research gaps is crucial to offer a new approach for the green energy progress in building. Therefore, there is a motivation for the author to investigate and assess the thermal potential of a shading façade-integrated solar absorber system as the problems mentioned above to complement the solar thermal concept in buildings.

As hypotheses,

H_{O1}: As the "rule of thumb" for the regions located in the northern hemisphere, the south oriented facades will receive high solar irradiance disregard the north orientation. In a low latitude region, however, the north oriented façade can potentially intercept a prominent amount of solar irradiance.

H_{O2}: Shading facade structure is a potential platform of integrating solar thermal collector which could possibly provide a sensible amount of solar thermal energy for heating the water of over 40 ^{o}C.

H_{O3}: The shading façade-integrated solar absorber system is capable to convert the incident solar energy into useful energy output with comparable efficiency as a conventional solar collector.

1.3 Objectives

The aim of this research is to harness incident heat on a building façade. In specific, the objectives are as follows:

(i) To determine the interception of solar radiation on various orientations of shading device under the low latitude climates in country to optimise its orientation.
(ii) To develop a numerical simulation of shading façade-integrated solar absorber system to analyse its geometrical and thermal characteristics.
(iii) To configure the system optimally by assessing its geometrical parameters and thermal performance.
(iv) To fabricate and demonstrate an experimental model of shading façade-integrated solar absorber to investigate the system model under hot tropical climate and to verify results.

1.4 Scope and Limitation

The scope and limitation of the present work are listed as follows:

(i) A simulation tool, MATLAB software, was employed in the development of numerical model based on theoretical considerations.
(ii) The well acknowledged literatures, (Duffie and Beckman, 2006; Klein and Theilacker, 1981), have been adopted as the references to develop the solar radiation algorithm model.
(iii) Twelve months in Julian calendar was undertaken in the simulation. A published solar radiation data bank for the location of Bandar Baru Bangi by Sopian and Othman (1992) was referred in the model simulation. The data was chosen due to its location which was the nearest to the site of the present study with merely 0^{o} 02' away in latitude. Besides, it was a long

term data that could sufficiently represent the actual local solar radiation level to best fit the solar model by Klein and Theilacker (1981).

(iv) The façade surface with azimuth angles from -180° to 180° was studied. Tilt angles from 0° in horizontal to 90° in vertical were within the scope to determine the interception of solar radiation.

(v) A basic layout of horizontal overhang shading device was chosen as a reference platform of integrating solar absorber due to its very common application in tropical and subtropical regions (Cheng et al., 2013; Hassan and Bakhlah, 2013). Despite the horizontal configuration could offer the good shading effect and interception of solar irradiance, this position might not be the optimum tilt angle for solar energy collection (Sun and Yang, 2010). Therefore, a louvre system in horizontal orientation was intended in the present work.

(vi) The size of horizontal extension required for full shading was determined based on the suggested solar time interval from 09:00 to 15:00, corresponding to the solar hour angle of ±45°. The duration is adequate corresponding to the overheated time frame with high solar intensity in tropics. Other similar research works have employed the same or lesser solar hour (Capeluto, 2003; Garg and Bansal, 1986; Palmero-Marrero and Oliveira, 2004; Paramita and Koerniawan, 2013).

(vii) The concept of flat plate collector was employed to develop the integration of solar absorber in the horizontal louvre shading facade. The configuration of the façade was designed based on the principle form of a standard flat plate collector (Duffie and Beckman, 2006) and recommendations by other researchers and manufacturer (Cheng et al., 2013; Mandalaki et al., 2012; Palmero-Marrero and Oliveira, 2010; Ralegaonkar and Gupta, 2005; RENSON®, 2013).

(viii) A typical and common residential building's window dimension of 600 mm (width) × 1200 mm (height) was adopted as a reference to define the sizing of the shading façade-solar absorber system (Al-Tamimi and Fadzil, 2011; Liping and Hien, 2007).

(ix) A shading façade-solar absorber model was fabricated with the identical physical scale of the simulation model. Outdoor experiment was conducted from May 2016 until November 2016. These periods are suitable for solar energy system tests (Azhari et al., 2008; Sopian and Othman, 1992).

(x) To achieve a sufficient actual outdoor data collection, 139 days data reading were collected throughout the seven months. It was adequate for the outdoor test referred to several experimental studies that were carried out in a relatively shorter period (Amin et al., 2009; Chong et al., 2009; Tang et al., 2008; Zambolin and Del Col, 2010). The time setting in the data logging devices was set to the actual local clock time referring to Malaysian Standard Time provided by SIRIM (2016).

(xi) It should be noted that the rain-repelling, illumination and excessive wind speed were not taken into account in the present work as there were no data available due to the limited facilities (Ahmed and Wongpanyathaworn, 2012). The shading performance on improving indoor thermal comfort of a building was also out of the scope in the present study.

1.5 Significance of Study

The significance of this research is a novel development of shading façade-integrated solar absorber system. The study intends to disclose the potential of the integrated system that might not merely serve to block excessive solar gain but potentially harness solar energy for thermal application. As limited knowledge is available in this area, it is expected to present findings in the use of solar collector façade integration strategic operated under local environment as the knowledge and information to the party of interest such as architects, engineers, industries and general public about its characteristics and performance. The established theoretical and experimental models could be useful, workable and practical for real case study of pilot scale subjected to evaluation. Finally, the knowledge is not limited to the shading structures, but possibly extend to other standard building facades with high solar exposure to harness the solar thermal energy on building envelope for sustainable application.

1.6 Thesis Layout

The thesis is organised into six chapters. Chapter 1 is general introduction, which presents the research motivations, problem statement, objectives, research questions, scope and limitation and significance of the study. Chapter 2 discusses literature related to the solar energy study, building architecture and solar heat transfer mechanism that are previously carried out by other researchers. This chapter contains the reviews of solar radiation in Malaysia, solar geometry, solar irradiance on building orientation, orientation of solar absorber, building integrated solar thermal systems, shading façade, solar collectors, solar water heating methods, flow arrangement of solar collector, performance analysis of solar collector and computational numerical methods. The overall methodological approach of the research work is presented into two chapters, Chapters 3 and 4. Chapter 3 presents the theoretical considerations, which the theoretical and mathematical model development of solar radiation model, shading façade-integrated solar absorber geometrical model, solar absorber model and the overall algorithm of system modelling are formulated and derived in detail holistically. Meanwhile, Chapter 4 demonstrates the materials and methods for the construction, system layout, control mechanism, outdoor experimental set-up and procedures of the shading façade-integrated solar absorber system model. Chapter 5 presents and discusses the numerical and experimental results of the system model in detail. Its economic aspect and potential application are depicted too. Finally, Chapter 6 contains the conclusion and recommendation for future work.

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